The performance of a solar air pre-heater system for the ventilation of two commercial poultry barns

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Abstract

Energy is one of the biggest concerns of today's society, because of the rapid depletion of the world's fossil fuel reserves. Efficient energy technologies and renewable energy sources must therefore be developed and implemented. With a 5% share of the total energy consumption, agriculture can benefit from such developments. To preheat cold and fresh ventilation air for livestock barns, solar collectors are one of the promising renewable energy sources to reduce fossil fuel used in heating. Besides identifying energy saving strategies, the objective of the present project was to evaluate the performance of a specific type of solar air pre-heaters consisting of unprotected black corrugated metal sheeting with 1% perforation, installed over the barn fresh air inlets facing south. In this experiment, the two identically built commercial broilers barns were located in St-Jean-Baptiste, 40 km east of Montreal, Canada at 45.5 ° latitude. Each barn offered three floors with a capacity of 6500 broilers/floor, and 73.65 m^2 of solar air pre-heaters for a total of 221 m^2/barn. From November 2007 to March 2009 the project monitored inlet, inside and outside air conditions, ventilation rate and solar energy recovery and, from this data, conducted energy balance analyses. Measured efficiencies in recovering solar radiation varied from 65% to 20% depending on wind velocity and produced an annual return on investment of 4.7%. Air temperature stratification inside each room was responsible for the loss of 25 and 15% in heater energy and recovered solar energy, respectively. Although reducing heating load, the solar air pre-heaters had no impact on livestock performance because of limited effect on ventilation rate. The monitoring of ambient air temperature and relative humidity was complicated by air temperature stratification. Furthermore, the proper monitoring of ventilation rates requires the installation of electromagnetic sensors on all exhaust fans. The pyranometers used in this experiment were able to measure solar radiation with a maximum error of 7%.

Résumé

L'énergie est l'une des plus grandes préoccupations de la société d'aujourd'hui en raison de l'épuisement rapide des réserves de combustibles fossiles dans le monde. Des technologies nouvelles et plus efficaces ainsi que des sources d’énergies renouvelables doivent par conséquent être développées et implantées. Avec une part de 5% de la consommation mondiale d’énergie, l’agriculture peut bénéficier de ces développements. Pour préchauffer l’air frais entrant par la ventilation des bâtiments d’animaux d’élevage, les capteurs solaires sont une des sources d’énergies renouvelables prometteuses afin de réduire la consommation d’énergie en chauffage. Outre l’identification des stratégies d’économie d’énergie, l’objectif de ce projet était d’évaluer la performance d’un type spécifique de capteurs solaires pour le préchauffage de l’air constitué d’un revêtement métallique noir, ondulé et non protégé du vent ayant 1% de sa surface en perforation. Ce revêtement était installé aux prises d’air d’un bâtiment dans la direction la plus méridionale possible. Les deux poulaillers étudiés au cours de cette expérience étaient identiques et exploités de façon commerciale. Ils étaient situés à St-Jean-Baptiste, à 40 km à l’est de Montréal, au Canada à une latitude de 45.5^{o}. Chaque bâtiment comprenait trois étages ayant un capacité 6500 poulets par étage et un système de capteur solaire de 73.65 m^2 chacun pour une aire totale de 211 m^2 par poulailler. De novembre 2007 à mars 2009, les caractéristiques de l’air dans les entrées d’air, à l’intérieur et à l’extérieur ainsi que le taux de ventilation et la radiation solaire ont été mesurés et analysés pour faire un bilan énergétique. Les efficacités de la récupération de chaleur provenant du rayonnement solaire ont varié de 65% à 20% dépendamment de la vélocité du vent, en plus les capteurs ont produit un retour sur l’investissement annuel de 4.7%. La stratification de la température de l’air sur chaque étage était responsable de la perte de 25% de l’énergie en chauffage et 15% de l’énergie solaire récupérée.

Bien que les capteurs solaires aient permis une réduction du temps de chauffage, aucun impact sur les performances des animaux n'a été remarqué en raison particulièrement d'un effet limité sur le taux de ventilation. L'acquisition des données de température ambiante et d'humidité relative a été compliquée par la stratification des températures de l'air. De plus, pour assurer un bon suivi des taux de ventilation, l'installation de capteurs électromagnétiques sur tous les ventilateurs serait nécessaire. Les pyranomètres utilisés dans cette expérience ont pu mesurer le rayonnement solaire avec une erreur maximale de 7%.

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Authorship and Manuscript

This thesis is written in a manuscript-based format. The contributions of authors are: 1) planning and executing experiments, equipment installation, maintenance and removal, performing calculations and analysis, and writing of manuscripts (student). 2) Supervising thesis work and reviewing of manuscripts (supervisor).

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Chapter 1: General Introduction

1.1 Problem Statement

The combustion of fossil fuels has caused several global environmental problems (Wen et al. 2009) such as: the production of greenhouse gases (CO_2, SO_2, NO_x), higher levels of acid rain and air pollution, ozone layer depletion and global warming (Turanjanin et al. 2009). Currently, non-renewable fuels are at the forefront of the debate related to environment and energy (Jacobsson and Johnson 2000). The global problem is amplified by future expectations of a considerable increase in power and heat demand (Shpirt and Goryunova 2009). This is especially true for developing countries such as China, India and Brazil which are using fossil fuel to fulfill their growing energy demand (Shpirt and Goryunova 2009). Despite an awareness of the negative impacts of fossil fuels, many countries such as Canada are ranked high in terms of CO_2 emissions/capita. With some 4.8 metric tons of carbon produced/person/year (Boden et al. 2009), Canada's high ranking results in large part from oil sand extractions in the province of Alberta. The extraction of bitumen combined with the upgrading processes is highly energy-intensive and generates significant CO_2 emissions. The oil sand industry also has the largest growth in greenhouse gas emissions in Canada (Ordorica-Garcia et al. 2008). Besides CO_2 emissions produced during extraction, the oil by itself produces greenhouse gases when combusted.

In Canada, the transportation sector plays a critical role in the economy but also in the emissions of CO_2. Roughly one third of Canadian's end-use energy demand is for the transportation of goods or for personal travel (National Energy Board of Canada 2009). In the United States, transportation is the second most demanding sector, after electricity generation, with 27.8% of the U.S. total demand where 97% of this energy is gasoline (95%) and natural gas (2%) (U.S. Energy Information Administration 2008). Despite such high consumption of energy, the transportation sector is forecast to increase its energy demand. According to prediction, the number of vehicles around the world will increase from approximately 1 billion in 2007 to 2 billion by 2030 (National Energy Board of Canada 2008).

The residential and commercial sectors are other large consumers of fossil fuel. In 2008, for these sectors, 92% of the total energy demand in the U.S. was supplied by fossil fuels and natural gas (U.S. Energy Information Administration 2008). Therefore, the heating and air-conditioning of residential, commercial and agricultural buildings generate an important amount of CO_2.

With the present fossil fuel world demand of 85 million barrels of oil/day (U.S. Energy Information Administration 2006) and its predicted increase, the world fossil-fuel resources will not be infinite. By keeping current consumption patterns, the total world oil reserves of 1316 billion barrels will be depleted by about 2050 (U.S. Energy Information Administration 2007b).

Solutions are needed to curtail greenhouse gas generation from fossil fuel burning and to prevent oil shortages in the near future. The first solution is to increase the efficiency of fossil fuel combustion processes by technical improvements. For example, the weight of vehicles such as cars, trucks, buses, trains, planes and boats, can be reduced by using new lighter and stronger materials where longer distance can be travelled with the same quantity of fuel. In parallel, motor fuel consumption can be improved. Energy required to heat and air-condition buildings can also be reduced by improving insulation, designs and using new construction concepts reducing air infiltration.

Renewable sources are another alternative to fossil fuel, although their present uses are limited especially in North America, renewable energies come in different form such as hydraulic power, biomass energy, geothermal power, wind power and sun power (Schilling and

Esmundo 2009). Water power is the simplest and most interesting forms of renewable energy. Conventional turbines, generating hydro-electricity from dammed water, currently provide worldwide 16% of all electrical power demand, representing 3000 billion kW-h (U.S. Energy Information Administration 2007a). Tidal power is another source of energy associated with water. Free-standing tidal stream turbines generate, in the United Kingdom, 10% of present electricity demand (Burrows et al. 2009). High-carbon wastes and crops can be used to produce biomass energy especially useful for heating. Examples of such biomass are solid and liquid municipal wastes, manure, wasted lumber and pulp mill residues, and forest and agricultural residues. However, this biomass can require some form of transformation prior to utilisation as a fuel and these processes lower their net energy values. Mainly used for heating buildings, geothermal power simply retrieves the Earth's internal underground heat. Over the past year, wind power was the fastest growing source of renewable electricity. In 2007, wind power accounted for 4% of the total energy demand in Europe (Roques et al. 2009). Sun power is the renewable energy with the largest potential with a total incident solar energy of 173,000 terawatts reaching the earth's surface. This energy level is equivalent to 17000 times the entire planet's consumption in fossil fuels (Abbasi and Abbasi 2009). However, solar power recovered by photovoltaic cells and simply black surfaces accounts only for a small fraction of the total energy demand. Already, several devices on the market allow the recovery of this huge source of energy. Heaters installed on building vents to reduce heating energy consumption are a good example. These solar collectors were originally developed for commercial and industrial buildings to preheat incoming fresh ventilation air.

Nowadays, the agricultural sector also tries to use greener energies to reduce fossil fuel dependence. In the winter, agricultural buildings are generally heated with propane or natural gas. However, there are incentives to use renewable energy sources such as solar air pre-heaters for the ventilation of livestock buildings with a high heating load.

1.2 Objectives

The main aim of this study was to evaluate the agricultural potential of solar collectors to preheat fresh ventilation air for livestock buildings. More specifically, the projects had the following objectives:

1) to evaluate the agricultural potential and heat recovery efficiency of unprotected solar air pre-heater installed over the fresh air ventilation inlets of two broiler barns;

2) to conduct a heat balance on two commercial broilers barns equipped with unprotected solar air pre-heaters over their fresh air inlets, to measure bird heat production under commercial compared to laboratory conditions, to measure the impact of the solar pre-heaters on ventilation rate, heat load and bird performance and to identify strategies to reduce winter heating load;

3) to review the building instrumentation system and strategy used in this project and recommend improvements for future work with a similar objective.

Installed on two commercial broiler barns in St-Jean-Baptiste, Canada, the experimental solar air pre-heaters consisted of unprotected black corrugated metal sheeting with 1% perforation installed over the fresh air inlets of the buildings facing south. The incoming cold fresh air was pulled over the black sheeting, through the perforations and behind the black sheeting to pick up solar energy before entering into the broiler barn. Also, the solar air pre-heaters could be bypassed by opening the bottom portion of the wooden framed boxes.

1.3 Scope

This study was conducted in St-Jean-Baptiste, 40 km east of Montreal, Canada, at 45.5 ° latitude. This experiment was conducted using two commercial and identically built broiler barns that were part of a group of 12 parallel broiler barns owned by La Coop Fédérée. From November 2007 to April 2009, a total of 6 batches of birds were grown during a period of 35 to 45 days, in an all in all out fashion. Each building had 3 floors and each floor was equipped with solar air pre-heater measuring 1.47 m in height and totalling 50.1 m in length for a total solar air pre-heater area of 73.6 m^2/floor or 221 m^2/building.

1.4 Thesis Format

Chapter 1 presents issues associated with the use of fossil fuels and suggests replacement solutions. Fossil fuels have introduced issues of air pollution created from their combustion and the release of greenhouses gases into the atmosphere. Furthermore, international reserves will soon be insufficient considering the increasing world demand for energy. Using fossil fuels more efficiently and introducing renewable sources of energies could solve some of the fossil fuel issues. Following this introductory chapter, Chapter 2 provide a literature review further exploring the fossil fuel issues and focusing on the agricultural sector. Efficiency and renewable energy sources are investigated for the agricultural building sector. Chapter 3 is a paper evaluating the energy recovery efficiency and potential of unprotected solar collectors to preheat the fresh ventilation air of broiler barns. Chapter 4 is a paper conducting a heat balance analysis to quantify broiler chicken heat production under commercial as compared to laboratory conditions, to measure the impact of the solar air pre-heaters on ventilation rate, heat load and bird performance, and to identify strategies to reduce winter heating load. In Chapter 5, a last paper evaluates the performance of the simple data acquisition system used to conduct heat balances on livestock buildings: this simple data acquisition system consisted of a set of instruments installed to measure inside and outside air conditions. Chapter 6 is a general conclusion reviewing the outcomes associated with each one of the three main objectives. Tables, figures and references are provided at the end of each chapter.

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Chapter 2: Literature Review

2.1 Introduction

The use of fossil fuel dates back to the last few millennia. The Chinese were among the first to refine crude oil to fuel lamps and heat homes. The use was limited and negligible compare to today's world oil consumption. Since the Industrial Revolution in the late eighteenth century, fossil fuel became more extensively utilized. During that period, coal steam engines were required to operate factories for textile manufacturing, locomotives and steamboat for the transportation of goods and people, and coal stoves in household for heating and lighting (U.S. Energy Information Administration 2009a). In the late 19th century, the rapid adoption and spread of the internal combustion engine for transportation created a growing need for fossil fuels and the world petroleum consumption has been increasing ever since (U.S. Energy Information Administration 2009a).

Today, fossil fuels are used everywhere and for numerous applications such as transportation, heating, lighting, and cooking. Most countries around the world now depend heavily on this resource as an energy source and also to grow economically. On a daily basis, 85 million barrel of oil/day are traded on the market to supply the present world demand (U.S. Energy Information Administration 2006). Moreover, emerging countries, such as China, India and Brazil, need more and more fossil fuel energy to fulfill their growing economic and heat demands (Shpirt and Goryunova 2009). Worldwide, 86% of the total energy production is linked to burning fossil fuels (Akorede et al. 2009). World consumption has reached a point where a major question must be asked: for how many more years can the reserves still supply the world?

According to the presently known world reserves of 1316 billion barrels, the current consumption pattern can be maintained until 2050 (U.S. Energy Information Administration 2007).

Fossil fuels offer many advantages over the other energy sources, presently available. Excluding nuclear energy, fossil fuels such as coal, natural gas and oil have a higher energy density than other energy source such as biomass. Fossil fuels are also more reliable than solar energy, wind and water power. However, fossil fuels have a dark side: they are causing several global environmental problems (Wen et al. 2009). The production of greenhouse gases such as CO_2, SO_2 and NO_x**,** higher levels of acid rain and air pollution, ozone layer depletion and global earth warming are all problems associated with fossil fuel combustion (Turanjanin et al. 2009). Due to its highest carbon intensity among fossil fuels, coal is producing almost 80% of the total CO_2 emissions for electricity production in United States while producing only 51% of the total world electricity generation (Akorede et al. 2009). Beside the CO_2 produced during combustion, the extraction of bitumen in tar sands is energy-intensive and generates a significant amount of CO_2. The oil sand industry is the principal contributor and explains the largest growth in greenhouse gas emissions in Canada. Coal steam turbines for electricity generation are the major supplier of CO_2 in the United States while also being the major producer of SO_2 (U.S. Energy Information Administration 2009a). Those greenhouses gases cause global warming by blocking infrared radiation from the Earth into space. Because SO_2 can be dissolve by atmospheric moisture, it is known that coal-fired plant along with diesel internal combustion engines are main contributors to acid rain causing important environmental concern (Akorede et al. 2009).

Despite the fact that today's world is dependent on fossil fuel, new energy sources must be developed could otherwise oil reserves could be depleted within the upcoming decades, global climate changes could cause catastrophes, and severe air pollution could result in extensive health problems for humans and ecosystems. Solutions to replace fossil fuel in the near future are definitely needed.

2.2 Improving Fossil Fuel Usage Efficiency in Building

A first step in reducing the environmental fossil fuel impact is to improve its usage efficiency in air conditioned buildings. Beside transportation, the production of electricity, and supplying energy for the industrial sector, the residential and commercial sectors account for 10.8% of the total fossil fuel demand in the United States (U.S. Energy Information Administration 2008a). The residential and commercial buildings have the biggest efficiency saving potential of 154 million tons of oil equivalent (Hull et al. 2009). A large amount of this energy can be saved by using conventional energy saving technologies. In new residential and commercial buildings, thermal insulation, low-emissivity windows, window overhangs and day lighting controls can decrease energy demand by 20-30% on average and in some building types and locations, up to 40% (Kneifel 2009). The energy improvement would save money, but also would reduce carbon emissions and free some electricity to replace coal-fired power plants.

The implementation of these energy efficient technologies will increase the construction cost of buildings. However, the energy savings over the years will more than compensate for the increased costs of energy efficient materials. Furthermore, additional savings can be achieved through smaller heating and/or air conditioning systems (Kneifel 2009). Investments in building for energy efficiency usually have short pay-back periods and negative net abatement costs (International Energy Agency (IEA) 2009).

2.3 Renewable Sources

Renewable energies are good solutions to replace fossil fuel energy. As compared to oil, coal and natural gas, renewable energies can be restored or reused. Only 7% of the total American energy consumption is supplied by renewable sources as compare to 84% for carbon-based energy (U.S. Energy Information Administration 2008b). Worldwide, fossil fuels are supplying 75% of total primary energy while renewable energy, mainly biomass and hydropower, provide only 19% (FAO 2000).

2.3.1 Biomass energy

Biomass is one of the renewable energies vastly used to replace fossil energy and mainly utilized in developing countries (Hall 1991). About 14% of the global energy production comes from biomass. However, this type of energy is not evenly distributed around the world as it represent only 3% of the total energy use in developed countries as compare to 33% in developing countries and 60% in Africa (FAO 2000). This energy source relies on plants to transform the sun's energy into chemical energy through the process of photosynthesis (Abbasi and Abbasi 2009). This chemical energy is stored in vegetation which can then be use as biomass energy. Even if the capture efficiency is generally about 1%, the total volume of biomass created represents 10 times our actual energy consumption (Abbasi and Abbasi 2009). Wood is one of the main energy sources consumed throughout the world where fossil fuels are not fully accessible, such as in developing and third world countries. In the United States, biomass is an important energy source since wood and biofuel represent 47% of the total renewable energy sources (U.S. Energy Information Administration 2008b). Nevertheless, biomass fuels are not totally clean energy sources, since they release greenhouse gases and often smoke and dust into the atmosphere. The intensive agricultural production of biomass could also lead to pollution from additional fertilizers, herbicides and insecticides usage (Schilling and Esmundo 2009).

2.3.2 Water power

Hydropower is another important renewable energy source as it transforms, without any destruction of the resource, flowing water into electricity. This energy is mostly produced through dams built on large rivers but can also be captured from the flow of water in the form of waves or by the water level differentials from tides (Schilling and Esmundo 2009). About 20% of the world power generation comes from hydropower and it is the main energy supply in 55 countries, especially to produce electricity (Kaygusuz 2009). Hydropower is also a good way of supporting other intermittent renewable energy sources such as wind and solar power as it can improve electric grid stability with its immediate response to fulfill peak power demand (Kaygusuz 2009). However, hydroelectric dams transform rivers into lakes, which alters and can disrupt the local environment by causing fish migration problems, increased soil erosion and water stratification, depleting oxygen from deep waters and affecting the livelihood of aquatic life (Schilling and Esmundo 2009).

2.3.3 Wind power

Wind power is the renewable energy source with the fastest growth over the past decade and particularly in Europe. Worldwide, wind power capacity exceeded 93 GW in 2007 where 57 GW, representing more than half the global production, was installed in Europe (Roques et al.

2009). Wind turbines are generally used to produce electricity and their technological improvement has increased power generation. Wind potential is especially feasible where high winds are present since the power increases as the cube of wind velocity. In the United States, the total potential wind energy resource is equivalent to the fossil fuel consumption (Schilling and Esmundo 2009). Nevertheless, only 1.7% of the total electricity demand in the United State is supplied by wind (U.S. Energy Information Administration 2009b) while Canada produced only 3.6TW.h. representing 0.6% of the total electrical production in 2008 (National Energy Board of Canada 2009). In Europe, wind power is much more exploited with a production of 4% of the total electrical demand in 2007 (Roques et al. 2009). However, wind power has its downside. Wind farms are often considered noisy, unsightly, and a potential nuisance to migratory birds. Moreover, wind power is not constant and the best wind sites are not usually close to urban areas, requiring the implementation of costly transmission equipment (Schilling and Esmundo 2009).

2.3.4 Solar power

Solar power is the cleanest source of renewable energy as it does not produce emissions and disrupt the physical environment (Schilling and Esmundo 2009). The immense potential of solar energy is equivalent to 17000 times the daily global energy need (Abbasi and Abbasi 2009). However, it is neither possible nor desirable to capture all this energy since most of sun's rays are simply reflected or captured by biomass. Solar energy has many applications such as to generate electricity, heat water and condition the air of buildings (Kalogirou 2004b). To supply electricity from sunlight, photovoltaic cells are needed. They convert the sun's photons into electricity via semi-conductive materials such as amorphous silicon, crystalline silicon and cadmium telluride. It is estimated that the use of commercial photovoltaic modules with an average efficiency and covering 270 km^2 (100 square miles) in Nevada would supply the electrical needs of the United States. The cost of photovoltaic modules is the main restriction preventing the intensive implementation of solar panels with a cost of 18 to 31 cents/kWh which is about 5 times more expensive than wind mills (Schilling and Esmundo 2009).

In the European Union, about 40% of the total energy consumption by buildings is spent to produce hot water and heat spaces (Kalogirou 2004a) and solar power can help reduce the amount of fossil fuel required for such tasks. Solar heating systems absorb solar radiation to transfer the heat to a fluid such as water, non-freezing liquids or simply air circulated through the collector. The heated fluid can be stored or used instantly. The energy can be collected directly by the circulating the fluid inside the collector or indirectly using a heat exchanger between heated fluid in the collector and the fluid transferring the energy source. Fluid circulation can be achieved with a passive system using natural convection or by an active system using a pump or a fan (Kalogirou 2004b). The capacity of presently available commercial industrial solar hot water system can reach 110 m^3 of hot water at 85^{o}C on sunny days, and reduce oil consumption by 78% (Nagaraju et al. 1999). Solar energy systems such as solar water heaters and space heaters are mainly used in countries with an excellent solar radiation potential (Kalogirou 1 2004). Solar heaters and photovoltaic cells produced only 1% of all renewable energy produced in U.S. in 2008 (U.S. Energy Information Administration 2008b).

2.3.5 Solar air heater

The present paper focuses on solar air heaters as a renewable energy source to heat the fresh and cold air used to ventilate buildings. The solar collector of interest consists of a perforated black corrugated metal siding installed 20 cm away from the south facing wall, creating a space where the air is pulled by the ventilation system. This type of solar collector is also called an ‘unglazed transpired plate collector. Large scale system have been installed and successfully operated for the preheating of fresh ventilation air in several countries such as Canada, the United States, Germany and Japan (Gunnewiek et al. 1996). This principle is robust, cost effective and virtually maintenance free compared to other solar air heating systems. Because the collector is unglazed, wind turbulence can affect its solar heat recovery efficiency (Fleck et al. 2002). Some studies showed that with a good design and a suction face velocity exceeding 0.02 m/s on the collector face exposed to wind, efficiencies in the high range of 75% can be obtained. However, with lower suction face velocities, wind turbulence lowers efficiency to a range of 65 to 20% (Fleck et al. 2003). Also the design of the collector should be optimized to create a uniform suction over the entire plate. Failing to create this uniform flow, the suction can be reversed over part of the collector which reduces the total energy efficiency (Gunnewiek et al. 2002).

2.4 Energy in Agriculture

2.4.1 General

Agriculture is an important energy consumer in developing and developed countries. Estimates suggest that the agricultural sector requires 3 to 5% of the total energy consumption worldwide and slightly higher with 4 to 8% of that consumed in developing countries. This percentage excludes the energy required for food processing and transport, which when included, doubles the energy demand (FAO 2000). In agriculture, mechanical, electrical and thermal energies are needed mostly for land preparation, crop implementation, fertilization, irrigation, harvesting, transport, building heating, crop drying, processing and storage.

2.4.2 Renewable energy sources from agriculture

The agriculture sector is not only an energy consumer, but an interesting potential producer of renewable energy. The most common energy provided by agriculture is biomass representing only 1% of the total mass output by agriculture worldwide (Mathews 2009). The three main sources of biomass are: liquid biofuel such as bioethanol and biodiesel, and; bio-oil and solid biofuels such as pelletized wood or residues (Mathews 2009). Biomass energy can be converted into electricity, gas, liquid fuel and heat while providing rural employment and increasing the profitability of the agricultural sector.

Wood used as biomass is in agricultural production in Europe. Fast-growing species of trees are cultivated and harvested every 2-3 years, to produced chips used as boiler fuel. Being cultivated or produced from forest residues, the majority of woodfuels are not associated with deforestation. A well managed wood energy supply can be a sustainable resource with an interesting economic potential (FAO 2000).

In the Americas, ethanol biofuel was originally produced using grain corn. However, advanced biofuel technologies can now produce ethanol from herbaceous and woody crops, with lower greenhouses gas emissions and less impact on food prices as compared to corn and wheat based biofuels (Jiang and Swinton 2009). Sugarcane in Brazil and grain corn in the United States are considered sources of biofuel using only 1% of the total cultivable surfaces (8 millions ha and 7 millions ha respectively) (Mathews 2009). Moreover, the agricultural sector can benefit from growing certain types of trees, perennial grasses or crops as biomass on abandonned, marginal and degraded land to increase biomass production without affecting food production (Schroder et al. 2008; Muller 2009).

Wind farming was introduced in North America early in the 20th century to pump water and directly generate power on farms. In developing countries, wind energy is still used to pump water for drinking and irrigation, to refrigerate produce and to power small local industries in villages located away from the national grid (Ojosu and Salawu 1990). Agriculture and wind power are a good combination since wind mills do not use a large land base. Accordingly, rural regions can benefit economically from such development by creating jobs, increasing local spending and producing returns on investment (Costanti 2004). Offshore wind power can be used by marine aquaculture to process fish and seafood, while reducing conflicting usages by combining two different ocean uses within the same area (Firestone et al. 2004). Moreover, windmill establishments are considered an investment by increasing land value and providing farmers with an additional income from a green energy source.

2.4.3 Solar energy in agriculture

Solar energy is vastly used in agriculture for among other applications, crop drying, greenhouses production, water desalination, electricity generation, and water and air heating. A 30% energy saving can be achieved when using solar air heating collectors to dry grain (Santos et al. 2005). In greenhouses, solar energy is a cost effective heating source on cold days. Even in Canada, significant amounts of solar energy can be captured to provide supplemental heating and lower production costs (Beshada et al. 2006). For dairy farms, large scale solar heaters can preheat water to produce hot water used in washing milking equipment (Anderson and Duke

2008). Finally, solar air heaters can be used to preheat the cold air used to ventilate livestock shelters requiring heating, such as a pig nursery, for an annual fuel saving of 0.12 to 0.18 CAN$/piglet.

2.4.4 Broiler barns

Canadian broiler barns have huge heating energy needs during the winter. High broiler chicken densities require a good ventilation rate to maintain, inside the barn, an acceptable level of air quality. Moreover, ambient air needs to be warm enough to ensure bird comfort with a temperature starting at 32^{o}C and dropping to no less than 24^{o}C. To maintain such high ambient air temperatures, the propane or natural gas heaters generally used rely on a good supply of fossil fuel (Shah and McGuffey 2008). To reduce the energy requirement and the emission of greenhouse gases, new alternative methods are being tested. Better shell air tightness and insulation leads to lower energy losses through conduction for greater building heating efficiency. Rather than operating on one or two speeds, variable speed exhaust fans consume up to 25% less power (Teitel et al. 2007). Another building improvement alternative is the replacement of older heating devices with newer and more efficient systems. In terms of using renewable energy sources in poultry barns, solar air heating systems have the capacity to preheat ventilation air and reduce winter heating loads as described in section 2.3.5 (Shah and McGuffey 2008). As compared to photovoltaic cells, transpired solar collectors are cheaper and thus more interesting as an energy production technique with a shorter payback period. According to the US Department of Energy, the temperature of the incoming fresh air can be increased by as much as 22^{o}C (Shah and McGuffey 2008).

2.5 Conclusion

Today's increasing world fossil fuel demand, and possible exhaustion of oil reserves within the next 50 years, requires the development of alternative energy sources. Despite being reliable and concentrated as an energy source, fossil fuel utilisation is responsible for present issues of global warming and atmospheric pollution. For those reasons, other energy sources must be introduced to replace fossil fuel within the next generation. Increasing efficiency in every consumption sector is one way to decrease fossil fuel utilisation and the residential and commercial building sector offers the greatest potential. Within the upcoming decade, fossil fuel consumption can also be replaced with or reduced by some promising alternative renewable energy sources.

Throughout the world and as a renewable energy source, wood is one of the most utilized biomasses, especially in developing countries. However, ethanol produced from sugar cane and corn is the preferred source of biofuel in industrialized countries. Using waterfalls and tides creating water level differentials, hydroelectric power is already vastly used. Wind energy is the fastest growing renewable energy and is mostly used to create electricity through wind turbine. Solar power can be recovered using two totally different technologies: photovoltaic cells converting solar energy into electricity, and; solar radiation heat collectors transferring the recovered heat to a fluid. Solar water collectors can preheat water or, with a heat exchanger, produce hot water. Solar air collectors to preheat cold fresh ventilation air can be coupled to high rate ventilation systems in buildings.

The fossil fuel consumption share of the global agricultural sector ranges between 3 and 5%. Accordingly, this sector must develop uses for renewable energy sources. Agriculture is already producing biomass for direct heat production or to generate biogas and liquid fuels such as ethanol. Farmers and aqua-farmers can benefit from the additional income generated by installations of wind turbines on their property, without sacrificing a significant land base. Solar energy is a promising energy source in agriculture and its use warrants further expansion. Solar collectors are already used by dairy farmers to preheat water to wash milking equipment and in heated swine and poultry barns to preheat fresh ventilation air. Due to the fact that heating is a major part of the production cost of poultry barns, solar air collectors can help reduce fossil fuel consumption and greenhouses gases emissions.

Although solar air collectors can recover an interesting level of energy during the winter to reduce heating loads, a limited number of farms are using this technology. A reason explaining such limited usage is the lack of economic justification. The popularity of solar air collectors could be improved if additional benefits could be demonstrated such as higher winter ventilation rates, with improved inside air quality and livestock performance. Accordingly, the present research project was designed to evaluate the performance of a specific solar heat collector design and its impact on winter ventilation rate and broiler chicken performance. At the same time, the project evaluated possible losses of energy and strategies to improve heating efficiency.

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Connecting Statement to Chapter 3

The main goal of this study was to evaluate the agricultural potential of the solar air pre-heaters. To do so, finding the efficiency of those collectors on the research site was essential. Chapter 3 examines the ways in which incoming solar radiation was measured along with the energy recovered by the solar air heaters.

This chapter is drawn from an article prepared for publication in the Journal of Renewable Energy. The manuscript was co-authored by Sebastien Cordeau, M.Sc candidate at McGill University and Dr. Suzelle Barrington, Supervisor and Professor at McGill University. The format has been changed to be consistent with this thesis.

Chapter 3: Performance of a solar ventilation air pre-heater for broiler barns

3.1 Introduction

Within a concept of sustainability, solar radiation is an interesting heat source for applications requiring a limited amount of energy. Despite the lack of research during the 1990's, the twenty-first century brought some renewed interest in solar energy to reduce the use of petro-fuels and their greenhouse gas generation. In agriculture, solar energy can provide heat for a wide range of applications.

While maintaining at 10°C the water temperature of a 3.5 tons/yr rainbow trout hatchery protected by a greenhouse structure in Winnipeg, Canada, 125 m^2 of flat plate solar collector reduced the energy requirement by 70% (Ayles et al. 1980). A similar system in Australia, also for a greenhouse protected fish hatchery, was able to reduce the heating load by 77% (Fuller 2007). Greenhouse orientation influences light transmission and inside heat dispersion when using a triangular roof with a 28° slope and 0.1 mm double polyethylene films glazing (Maghsood 1976). In southern Manitoba, Canada, the solar performance of a Chinese greenhouse was investigated where the north wall was well insulated and a thermal blanket was used as further night time protection. Without heating, the greenhouse inside air temperature remained above 1°C, despite cold winter nights of -29°C (Beshada et al. 2006).

For the drying of hay in the Canadian Prairie Provinces, solar energy could reduce heating and operating costs by 30 to 45% (Arinze et al.1993). In Ireland, solar radiation had an impact on the temperature distribution and thus the ventilation of agricultural products stored in silos (Jia et al. 2000). For a circular vertical wall silo with an inclined roof surface, models were successfully developed to accurately predict absorbed solar heat (Chang et al. 1993; Jiang and Jofriet 1987).

A 50% energy saving was observed in the heating of a swine gestation barn in Saskatoon, Canada, using a solar collector consisting of a black exterior wall covered by a glazing of corrugated clear fibreglass and exposed to the south (Sokhansanj and Schoenau 1991). The incoming cold ventilation air circulated over the face and back of the steel sheet to enhance radiation heat recovery. While the solar collector had a short payback period of 5 years, adding a solar heat storage system was not found to be economical. More recently, a 15 to 45% energy recovery was measured for unprotected solar air pre-heaters installed over the ventilating inlets of a swine nursery in the Quebec City area, Canada (Godbout 2004).

To further evaluate the agricultural potential of such unprotected solar air pre-heaters, in this study, the authors measured their efficiency in recovering solar radiation and reducing the heating cost of two broiler barns located 40 km east of Montreal, Canada. Each barn had three floors offering an area of 535 m^2/floor. Solar air pre-heaters covered a vertical surface of 73.65 m^2/floor on the southeast wall for a total of 221 m^2/barn. Besides a horizontal radiation sensor, a vertical radiation sensor was positioned parallel to the southeast barn walls to measure the absorbed solar radiation. Both radiation measurements were validated against the readings of the Varennes Environment Canada weather station located 30 km northwest and theoretical values, respectively (ASHRAE 2009). For the winters of 2007-08 and 2008-09, the efficiency of the solar air pre-heaters was measured by comparing the heat recovered by the incoming ventilation air and the solar radiation absorbed by the vertical radiation sensor parallel to the southeast barn walls. The savings in heating was also determined by monitoring the operation time of natural gas heaters on each floor.

3.2 Calculation method for incident solar radiation

The incident solar radiation received by a plane on the surface of the Earth is a function of its solar orientation and position. This plane will receive direct, indirect and diffused radiation, all of which can be calculated based on the following simplified method (ASHRAE 2009). This method was used to validate the measured absorbed radiation by a radiation sensor positioned vertically and parallel to the experimental barn walls on which the solar air pre-heaters were installed.

Because of time zones, the actual time must be converted to solar time, H in hour angle, where the sun is positioned directly south at noon

$$H = R \times (LST + ET/60 - 12) + LSM - LON \tag{1}$$

where LST is the local standard time in decimal hours, ET is the equation of time in decimal minutes, LSM is the local meridian time in decimal degree of arc, LON is the local longitude in decimal degree of arc and R is the earth's rotational velocity of 15 degree of arc/hour. The hour angle time H is simply the solar time before or after noon divided by 15 arc degree/hr.

For any given day of the year n and time on that day H in hour angle, the incident solar radiation is affected by the declination of the earth with respect to the sun, δ

$$\delta = 23.45° \times \text{Sin}\ (360/365 \times (284 + n)) \tag{2}$$

where δ is the sun's declination in degree of arc and n is the Julian day of the year where January 1st is $n = 0$ and December 31st is $n = 365$.

For a given day of the year, solar radiation occurs from sunrise to sunset, H_r and H_s, respectively. Considering that at H_r and H_s, the sun's altitude β is 0°

$$\text{Cos}\ (H_r) = \text{Cos}\ (H_s) = -\ \{\text{Sin}\ (L)\ /\ \text{Cos}\ (L) \times \text{Sin}\ (\delta)\ /\ \text{Cos}\ (\delta)\} \tag{3}$$

where H_r is equal to $-H_s$, all values of H_r, H_s and H are in hour angle before or after noon, and L is the latitude of the location in degree of arc. Between H_r and H_s, the sun's altitude β is computed as

$$\text{Sin}\ (\beta) = \{\text{Cos}\ (L) \times \text{Cos}\ (\delta) \times \text{Cos}\ (H) + \text{Sin}\ (L) \times \text{Sin}\ (\delta)\} \tag{4}$$

And the sun's azimuth Φ is calculated as

$$\text{Cos}\ (\Phi) = \{\text{Sin}\ (\beta) \times \text{Sin}\ (L) - \text{Sin}\ (\delta)\}\ /\ \{\text{Cos}\ (\beta) \times \text{Cos}\ (L)\} \tag{5}$$

The direct normal solar irradiation I (W/m^2) is computed as

$$I = A\ /\ e^{\{B/\text{Sin}\ (\beta)\}} \tag{6}$$

where A (W/m^2) and B (dimensionless) are factors defined by regression according to monthly values (ASHRAE 2009) depending on the day of the year n

$$A = -\,2.229 \times 10^{-7} \times n^4 + 1.648 \times 10^{-4} \times n^3 - 3.418 \times 10^{-2} \times n^2 + 1.387 \times n + 1214 \tag{7}$$

$$B = 1.140 \times 10^{-10} \times n^4 - 8.607 \times 10^{-8} \times n^3 + 1.884 \times 10^{-5} \times n^2 - 9.748 \times n + 0.1547 \tag{8}$$

The value of I can vary by as much as 15% (ASHRAE 2009) depending on the clearness of the atmosphere. Accordingly, the direct solar irradiation absorbed by a vertical plane E_{DN} , oriented at ψ degree from the south is defined in terms of the cosine of the incident angle θ

$$\theta = \mathrm{Cos}^{-1}\,[\mathrm{Cos}\,(\beta) \times \mathrm{Cos}\,(\Phi - \psi)] \tag{9}$$

and

$$E_{DN} = A \,/\, \mathrm{e}^{\{B/\mathrm{Sin}\,(\beta)\}} \times \mathrm{Cos}\,\theta = I \times \mathrm{Cos}\,\theta \tag{10}$$

The ground reflected radiation E_r (W/m^2) is computed as

$$E_\mathrm{r} = [A \,/\, \mathrm{e}^{\{B/\mathrm{Sin}\,(\beta)\}}\,] \times [\mathrm{C} + \sin(\beta) \times \rho_\mathrm{g}\,] \times 0.5 = I \times [\mathrm{C} + \sin(\beta) \times \rho_\mathrm{g}\,] \times 0.5 \tag{11}$$

where ρ_g is the coefficient of ground reflection, it is generally equal to 0.2 for mixed surfaces (ASHRAE 2009).

The diffused radiation is

$$E_d = [A / e^{\{B/\mathrm{Sin}\,(\beta)\}}] \times C \times y = \mathrm{I} \times C \times y \tag{12}$$

where C (dimensionless) is also a function of the day of the year n

$$C = -\,2.229 \times 10^{-7} \times n^4 + 1.648 \times 10^{-4} \times n^3 - 3.418 \times 10^{-2} \times n^2 + 1.387 \times n + 1214 \tag{13}$$

and

$$y = 0.55 + 0.437\ \mathrm{Cos}\,(\theta) + 0.313\ \mathrm{Cos}^2\,(\theta) \quad \text{for } \theta > -\,78\,° \tag{14}$$

Accordingly, a vertical plane oriented at ψ arc degree from the south will absorb the following direct, ground reflected and diffused solar radiation, R_a, equal to I multiplied by the sum of the respective coefficients

$$\begin{aligned} R_a &= I \times [Cos\,\theta + (C + \sin(\beta) * \rho_g) \times 0.5 + (C \times y)\,] \\ &= [A / e^{\{B/\mathrm{Sin}\,(\beta)\}}] \times [Cos\,\theta + (C + \sin(\beta) * \rho_g) \times 0.5 + (C \times y)\,] \end{aligned} \tag{15}$$

This last equation was used to validate the absorbed radiation measured by the vertical sensor installed on the weather station.

3.3 Method

3.3.1 Experimental materials and instruments

In this experiment, the two identically built broiler barns were located in St-Jean-Baptiste, 40 km east of Montreal, Canada, at 45.5 ° latitude where the *LSM* was 75.0° at normal eastern time, and the *LON* was 73.1°. The barns faced the southeast at an angle ψ of 50° from the south, and measured 9.2 m in width, 9.0 m in total wall height and 61 m in total length where 57.9 m was occupied by the broilers. The barns each offered three floors equipped with 5 solar air pre-heaters measuring 1.47m in height and totalling 50.1 m in length, for 73.65 m^2/floor or 221 m^2/barn. The solar air pre-heater consisted of an unprotected black corrugated metal sheet with 1% perforation through which ventilation air was sucked and circulated against its back before entering the barn through the ventilation inlet (Figure 3.1).

Each barn floor had a capacity of 6 500 birds raised in batches over 35 to 45 days from 0.035 to 2.5 kg in body weight. During the cold season and once the broilers were freshly introduced into the barns, only two 400 mm fans were operated on each floor at a minimum speed of 55%. The speed of these exhaust fans was increased by an automated control governed by the temperature measured using three thermocouples located in the centre but distributed over the room length (Figure 3.2), at 0.3 m off the floor. The speed of the 400 mm fans was increased from 55 to 100% over a temperature increment of 1.4°C. The temperature set-point started at 32°C and dropped by 0.27°C/day until it reached 24°C. After one to three weeks, a third 400 mm fan was placed in operation and all three fans handled the fresh air ventilation rate until the end of the batch. At 55 and 100% of their full speed, each 400 mm fan delivered 0.43 m^3/s

(CV=14.9%) and 0.94 m^3/s (CV=7.6%), measured using a Balometer (ALNOR EBT721 Balometer, Huntingdon Beech, CA, USA).

Installed on a tower 3.0 m high and located in a grassed area mid way between the two broiler barns, a weather station recorded the ambient climatic conditions, namely wind velocity and direction, ambient air temperature, barometric pressure and relative humidity, and absorbed radiation. A Hobo data logger (Hobo Energy Logger Pro data logger, Onset Computer Corporation, Pocasset, MA USA) recorded all weather data reading every 5 minutes and was downloaded monthly onto a portable computer. Two solar radiation sensors (Model S-LIB Hobo Silicon Pyranometer Smart Sensor, Onset Computer Corporation, Pocasset, MA USA) were placed in horizontal and vertical positions, to respectively measure the horizontally absorbed radiation and the radiation adsorbed by the solar air pre-heaters. The vertical radiation sensor was placed parallel to the solar air pre-heaters using a compass. According to the manufacturer, the Hobo silicon pyranometer radiation sensors measure absorbed radiation with a maximum error of ±10.0 W/m^2 or ±5%, whichever is greater in sunlight. An additional error of 0.38 $W/m^2/°C$ can be associated with temperatures above 25°C. The Hobo silicon pyranometer radiation sensors use silicon photodiodes to measure solar power with a spectral range of 300 to 1100 nm. Nevertheless, this range introduces a negligible error when the sensors are calibrated to measure natural sunlight (Onset Computer Corporation, Pocasset, MA USA). The accuracy of the vertical radiation sensor was verified by comparing its reading to theoretical values (ASHRAE 2009), while that of the horizontal sensor was verified against that of the Varennes Environment Canada weather station (Latitude of 45.7°) located 30 km northwest.

The air conditions on each floor of both barns were recorded every 5 minutes. The inside air temperature of each floor was measured at three positions located 0.3 m off the floor (T_1, T_2 and T_3), next to the thermocouples controlling the ventilation system (Figure 3.2). The incoming fresh air temperature was measured at two locations inside the fresh air inlets (T_5 and T_6). One more temperature sensor was installed at one of the 400 mm diameter exhaust fan in continuous operation (T_4). All temperature sensors were Smart Set Hobo sensors (Onset Computer Corporation, Pocasset, MA, USA).

The ventilation rate was monitored by recording the rpm of one 400 mm fan/floor using an electromagnetic converter (Heber et al. 2001). The air flow rate was computed from a correlation obtained using a Balometer (ALNOR EBT721 Balometer, Huntingdon Beech, CA, USA) during which the volumetric air displacement of all 400 mm fans was measured at rpms varying from 55 to 100%. Each floor was heated using two 30 kW natural gas heaters. The heating load was recorded every 5 minutes using a 5 volts AC adapter detecting gas heater operation and sending a signal to the data logger to record operating time.

3.3.2 Methodology

The main objective of the project consisted in measuring the heat recovered by the solar air pre-heaters and, thus, the savings in heating load during the two consecutive winters, namely from November 2007 to March 2008 and from December 2008 to March 2009, inclusively.

The efficiency of the solar air pre-heaters was monitored continuously by comparing the measured absorbed vertical radiation to the solar heat recovered by the cold fresh air at the ventilation inlet (ASHRAE 2009) and (Esmay and Dixon 1986). This heat recovery was computed from the difference in monitored exterior and fresh air inlet temperatures multiplied by the air flow rate of the ventilation system

$$\infty = [(T_t - T_o) \times Cp \times Q \times \rho_a] \quad (16)$$

$$\varepsilon = \infty \times 100 / [R_s \times A_w] \quad (17)$$

where ∞ is the energy recovery by the cold fresh air circulating over the solar air pre-heaters in kW, ε is the solar air pre-heater efficiency in%, T_t is the air temperature at the ventilation inlet in °C, T_o is the outside air temperature in °C, Cp is the heat capacity of dry air or 1.006 kJ/kg dry air per °C, Q is the ventilation rate offered by the ventilation system in m^3/s, ρ_a is the density of dry air for the temperature measured at the exhaust fan in kg/m^3, R_s is the absorbed radiation measured by the vertical sensor representing the potential heat which can be transferred to the cold fresh air by the solar air pre-heaters in kW, and A_w is the area of solar air pre-heaters of 73.65 m^2 /floor.

The solar air pre-heater monitoring started upon reception of each batch of young birds and terminated when the fully grown birds were sent for slaughter, in an all-in all-out fashion. The acquired data was downloaded onto a portable computer between bird batches. Infra-red pictures were also taken of the solar air pre-heaters from outside to visualize the uniformity in solar heat recovery.

3.3.3 Statistical analysis

Solar heat recovery efficiency was correlated to wind velocity using Excel (Microsoft Office 2007, Seattle, WA, USA).

3.4 Results

3.4.1 Validation of solar irradiance data

Figures 3.3 and 3.4 compare the absorbed radiation for a horizontal plane, measured at the Varennes weather station of Environment Canada and by the horizontal radiation sensor at the experimental site, for two clear days free of clouds. The values measured at the experimental site follow the same trend as those measured by Environment Canada except for the peak which was generally 5 to 7% higher at the experimental site. This resulted from the fact that the Varennes Environment Canada weather station was 30 km away from research site and sky conditions can be different even on clear days. Moreover, radiation sensors had an accuracy of 5% or 10W/m^2, whichever is larger.

Figures 3.5, 3.6 and 3.7 compare the absorbed solar radiation calculated using Equation (15), for a vertical plane parallel to the barn walls, to that measured by the vertical radiation sensor on April 6th and 7th, 2008, November 19th, 2007 and February 14th, 2009, respectively. The values measured at the experimental site followed the same trend as those calculated except for a 4% variation, resulting from the clearness of the sky which can create up to 15% variation (ASHRAE 2009). When the ground reflection coefficient ρ_g was adjusted with seasons and ground covering, Equation (15) produced values corresponding to the measured data after 3:00

pm, when the sensor was no longer exposed to direct solar radiation. On November 19th, 2007 with a light snow cover over frozen grounds and on February 14th, 2009 with a heavy snow cover, a value of 0.3 and 0.6 for ρ_g respectively provided a good data fit. On April 6th and 7th, the recommended value of 0.2 for ρ_g also provided a good fit. Considering that the 3.0 m high weather station was installed half way between the two experimental barns, 58 m apart and 11 m in total height with the roof, some shadow effect was observed from November to February inclusively, by the vertical sensor before 9:00 am (Figures 3.6 and 3.7).

Accordingly, the two Hobo silicon pyranometer radiation sensors were found to measure the absorbed radiation with a maximum error of 7%, including differences in air moisture content. This maximum error is considered adequate considering that depending on the clearness of the day, values can vary by as much as 15% (ASHRAE 2009).

3.4.2 Solar air pre- heater energy recovery efficiency

Figures 3.8 and 3.9 illustrate the effect of wind velocity on the energy recovery efficiency of the solar air pre-heaters for March 5th and 12th, 2009, respectively. The total energy absorbed, indirectly measured by the vertical solar sensor, is compared to that recovered by the cold fresh ventilation air at the inlet. Although the average ventilation rate on each day was 1.18 m^3/s and 1.16 m^3/s, the overall efficiency in energy recovery (Equation 17) was 63% and 20%, under respective wind velocities of 2.6 m/s and 7.2 m/s. Whereas both days experienced the same incident solar radiation, 30 kW of average energy was recovered on March 5th between 9:00 am and 1:00 pm, as opposed to 10 kW on March 12th because of stronger winds.

Figure 3.10 correlates solar air pre-heater efficiency and wind velocity irrespective of its direction when the solar air pre-heaters are either actively used or bypassed (Figure 3.1). The data from days with a low solar incident radiation under 15 kW, on the average between 8:00 am and 4:00 pm, are excluded because of limited wind effect. When the incoming fresh air was pulled through the solar air pre-heaters (active solar air pre-heaters), heat recovery efficiency was correlated to wind velocity (R^2 of 0.41) and dropped by 5.7% for every 1 m/s of incremental wind velocity. When the incoming fresh air bypassed the solar air pre-heaters, some energy was still recovered but the efficiency was under 20% and dropped by 4% for by every 1m/s of incremental wind velocity. Furthermore, a high wind velocity above 6.8 m/s practically eliminated all solar heat recovery when the solar air pre-heaters were bypassed. During the summer and despite bypassing the solar air pre-heaters, the temperature of the incoming fresh air increased by 1 to 2°C on average during the day time with ventilation rates exceeding those of the winter. Finally, the outside temperature and the barn ventilation rate had no apparent impact on the energy recovery efficiency of the solar air pre-heaters (R^2 of 0.05).

In this experiment, the ventilation rate remained generally constant at its minimum level of 0.86 and 1.17 m^3/s with two and three fans in operation, representing a solar pre-heater ventilation air surface speed of 0.012 or 0.016 m/s. This surface speed is close to the lower limit of recommended values of 0.017 to 0.039 m/s for long buildings such as those used in this experiment, to minimize wind effect when facing unprotected solar air pre-heater and at 45 ° respectively (Gunnewiek et al. 2002). Using a ventilation air flow rate of 0.01 m/s against the unprotected solar air pre-heater, average efficiencies of 40 to 50% were observed for wind velocities under 2 m/s and of 25% for wind velocities above 6 m/s (Fleck et al. 2002).

Furthermore, efficiency decreased with increasing levels of incident solar radiation but remained relatively stable irrespective of wind direction.

Despite the observed wind effect and during sunny days, the solar air pre-heaters substantially increased the temperature of the cold incoming ventilation air and dropped the heating requirements for the broiler barns. Figure 3.11 shows a heating load dropping by an average of 15 kW during 8 h on February 24th and 18.8 kW on February 25th, for a total energy saving of 432 and 540 MJ/day, respectively.

The solar air pre-heater energy exchange process was viewed on March 20th, 2009 using an infrared camera (Figure 3.12 and 3.13). The barn siding exhibited a temperature of 0 to 7°C corresponding to an exterior temperature of 0°C, while the solar air pre-heater exhibited a temperature of 10 to 18°C, with the stud support structure at 10 to 12°C. Over the air inlets, the solar air pre-heater exhibited a temperature of 22 to 25°C while the barn air temperature was at 32°C. During cold winter nights in the absence of solar energy, the air temperature inside the inlet was observed to be 1 to 2°C warmer than that outside. In Figure 3.8 a, the cold fresh air was observed to progressively pick up heat over the full surface of the solar air pre-heater indicating no preferential path with wastage of solar energy.

For the experimental period, the overall heat recovery performance of the solar air pre-heaters is summarized in Table 3.2. The highest average solar energy recovery efficiencies of 64.1 and 54.8% were reached in November/December of 2007 and 2008, respectively, when the incoming solar radiation was at its lowest level of 6.00 and 6.59 MJ/m^2/day, as also observed earlier (Fleck et al. 2002). During January/February and March of each year, the energy recovery efficiency ranged between 35 and 55%. Between years, the efficiency varied with sky cloudiness and wind velocity. Nevertheless, higher levels of incident radiation above 8 $MJ/m^2/day$ lead to more incoming fresh air heating and heating load reduction. Assuming an energy cost of CAN$ 0.08/kWh, the solar air pre-heaters were able to recover on the average, and from November to March of both years, an energy value of CAN$ 14.80/m^2, corresponding to a 4.7% annual return on investment, defined as the ratio of the annual average energy recovered and the initial investment cost.

3.5 Conclusion

The objective of the present paper was to evaluate the heat recovery efficiency and potential of an unprotected solar air pre-heater consisting of an unprotected black corrugated metal sheeting with 1% perforation through which cold fresh air was pulled and used to ventilate broiler chicken barns.

The radiation sensors used on the experimental site were found to measure the absorbed radiation with a maximum error of 7%, including the effect of variable exterior air moisture content. Furthermore, the theoretical method of predicting absorbed radiation on a vertical surface (ASHRAE 2009) was found to be adequate for a ground reflection coefficient ρ_g of 0.2 during the summer for a grass cover, and 0.3 and 0.6 during the winter for a light and heavy snow cover, respectively.

Wind velocity was found to be the main factor affecting the energy recovery efficiency of the unprotected solar air pre-heaters. The average efficiency of the solar air pre-heaters was 65%

for wind velocities under 2 m/s, but dropped below 25% for wind velocities exceeding 7 m/s. Overall, the solar air pre-heaters were able to recover CAN$ 14.80/m^2/cold season, representing an annual return on investment of 4.7%.

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Table 3.1. Nomenclature

A, *B* and *C* are coefficients changing with *n* and used to calculate the absorbed radiation, dimensionless.

A_w is the area of solar air pre-heaters of 73.65 m^2 /floor.

*C*p is the heat capacity of dry air or 1.006 kJ/kg dry air /°C.

CV is the coefficient of variation.

E_d is the diffuse solar irradiance in W/m^2.

E_r is the ground reflected solar irradiance in W/m^2.

E_{DN} is the absorbed direct solar irradiacne in W/m^2.

ET is the equation of time in decimal minutes.

H is the solar time before or after noon divided by 15 degree of arc/hr, where for example H is 0 degree of arc at noon.

H_r is sunrise in hour angle about noon.

H_s is sunset in hour angle about noon.

I is the incident radiation W/m^2.

L is the latitude of the location in degree of arc.

LON is the longitude of the position in decimal degree of arc.

LSM is the local meridian time in decimal degree of arc.

LST is the local standard time in decimal hour.

n is the day f the year, where January 1^{st} is $n = 1$ and December 31^{st} is $n = 365$.

Q is the ventilation rate offered by the ventilation system in m^3 / s.

R is the earth's rotational speed of 15 degree of arc/hr.

R_a is the absorbed solar radiation in W/m^2.

R_s is the absorbed radiation measured by the vertical sensor representing the potential heat which can be transferred to the cold fresh air by the solar air pre-heaters with an area of 73.65 m^2/floor.

T_t is the air temperature at the ventilation inlet in °C.

T_o is the outside air temperature in °C.

WS is wind velocity in m/s.

y is a coefficient used to describe the diffused absorbed radiation, dimensionless.

β is the sun's altitude in degree of arc.

Φ is the sun's azimuth measured from the south in degree of arc.

δ is the declination of the earth with respect to the sun in degree of arc.

∞ is the energy recovery by the cold fresh air circulating over the solar air pre-heaters in kW.

ε is the solar air pre-heater efficiency in%.

θ is the angle of incidence of the solar radiation on the absorbing surface in degree.
ρ_g is the coefficient of ground reflection generally equal to 0.2.

ρ_a is the density of dry air for the temperature measured at the mouth of the fan in kg/m^3.

Ψ is the orientation of the vertical wall receiving the radiation and with respect to the south in arc degree.

Table 3.2. Solar air pre-heater performance.

Month	Expected***	St Jean Baptiste 2007	St Jean Baptiste 2008	St Jean Baptiste 2009
January – February				
- Vertical incident radiation* (GJ / (MJ/m^2/day))	21.5/9.4		20.3/8.8	23.2/11.2
- Increase in air inlet temperature (°C)			3.1	6.2
- Solar air pre-heater efficiency (%)			**36.6**	**42.5**
- Average day time ventilation rate (m^3/s)			1.16	1.28
- Solar energy recovered at the inlet (Can. $/barn/day)			$15.80	$23.40
March				
- Vertical incident radiation* (GJ / MJ/m^2/day)	27.0/11.8		37.4/16.3	28.1/12.2
- Increase in air inlet temperature (°C)			8.55	4.9
- Solar air pre-heater efficiency (%)			**53.6**	**35.3**
- Average day time ventilation rate (m^3/s)			1.28	1.17
- Solar energy recovered at the inlet (Can. $/barn/day)			$42.90	$21.15
November – December				
- Vertical incident radiation* (GJ/ MJ/m^2/day)	14.8	13.8/6.0	15.1/6.59	
- Increase in air inlet temperature (°C)		4.3	3.8	
- Solar air pre-heater efficiency (%)		**64.1**	**54.8**	
- Average day time ventilation rate (m^3/s)		1.17	1.16	
- Solar energy recovered at the inlet (Can. $/barn/day)		$18.90	$17.70	
Total solar energy at the inlet (Can. $/barn/winter season)			$3 415	$3 115

* for the south east wall orientation of the building with 73.65 m^2 of solar air pre-heater; ** Environment Canada;
*** average solar radiation for the Montreal area according to Natural Resource Canada. The solar energy recovered at the inlet is based on a value of $0.08 Can./ kW-h; one season covers the period of Nov. to March inclusively.

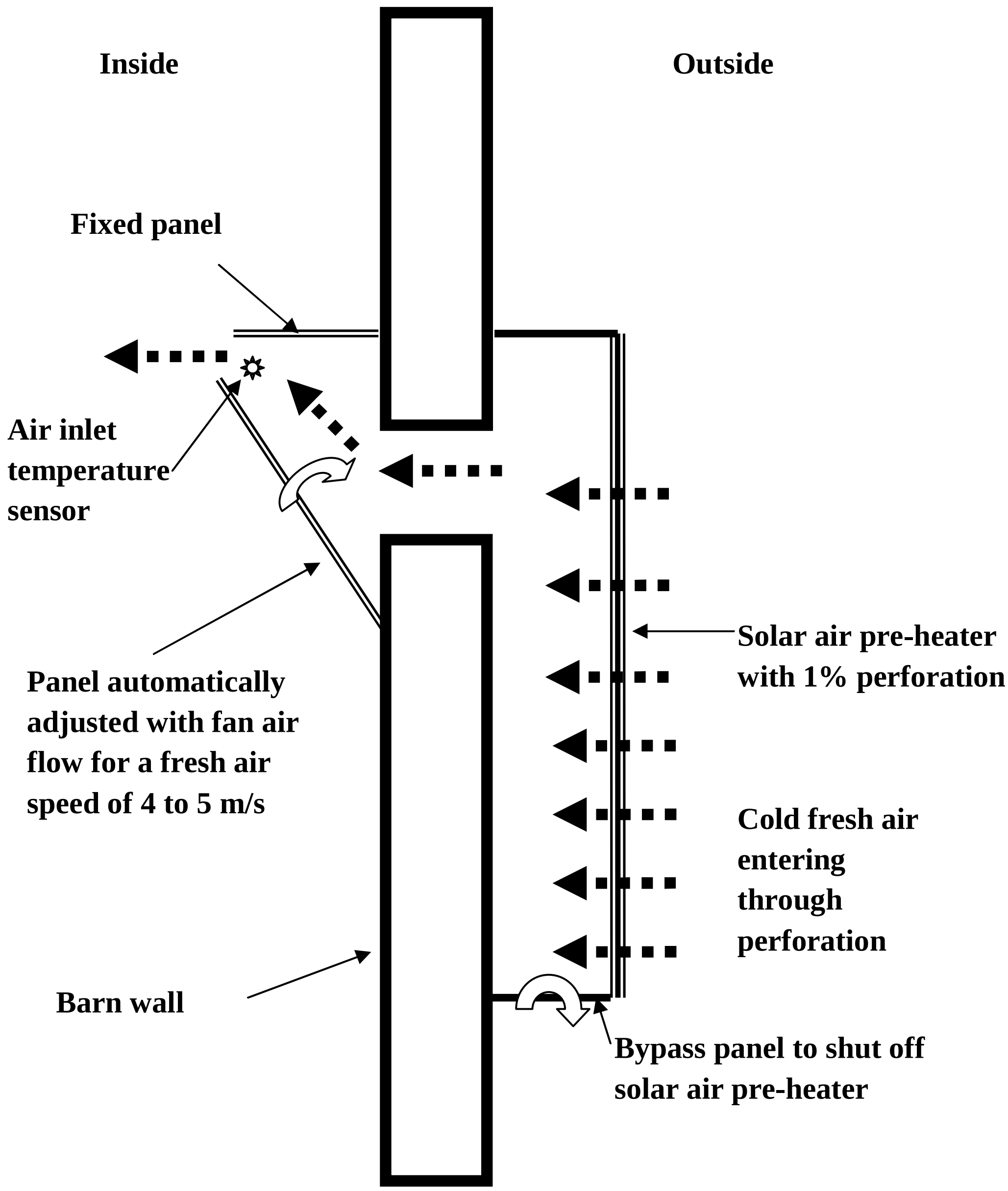

Figure 3.1: Configuration of the experimental solar air pre-heaters built of corrugated black metal siding.

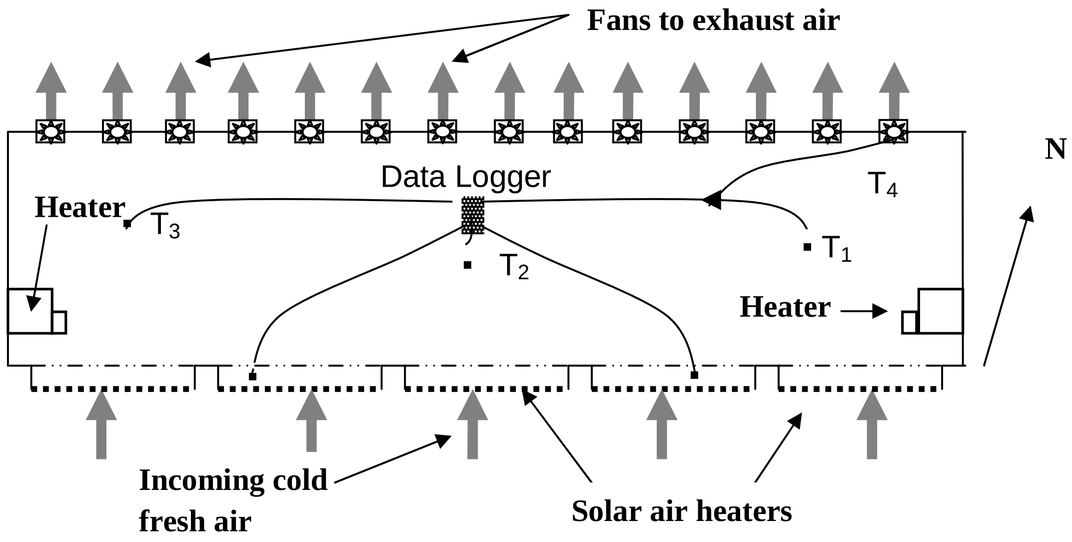

Figure 3.2: Instrumentation of experimental barns where: T_1, T_2, T_3 are air temperature sensors installed inside at 0.3 m off the floor; T_5 and T_6 measure the fresh air inlet temperature after the solar air pre-heaters, and; T_4 measures the outgoing air temperature at the exhaust fan operated continuously.

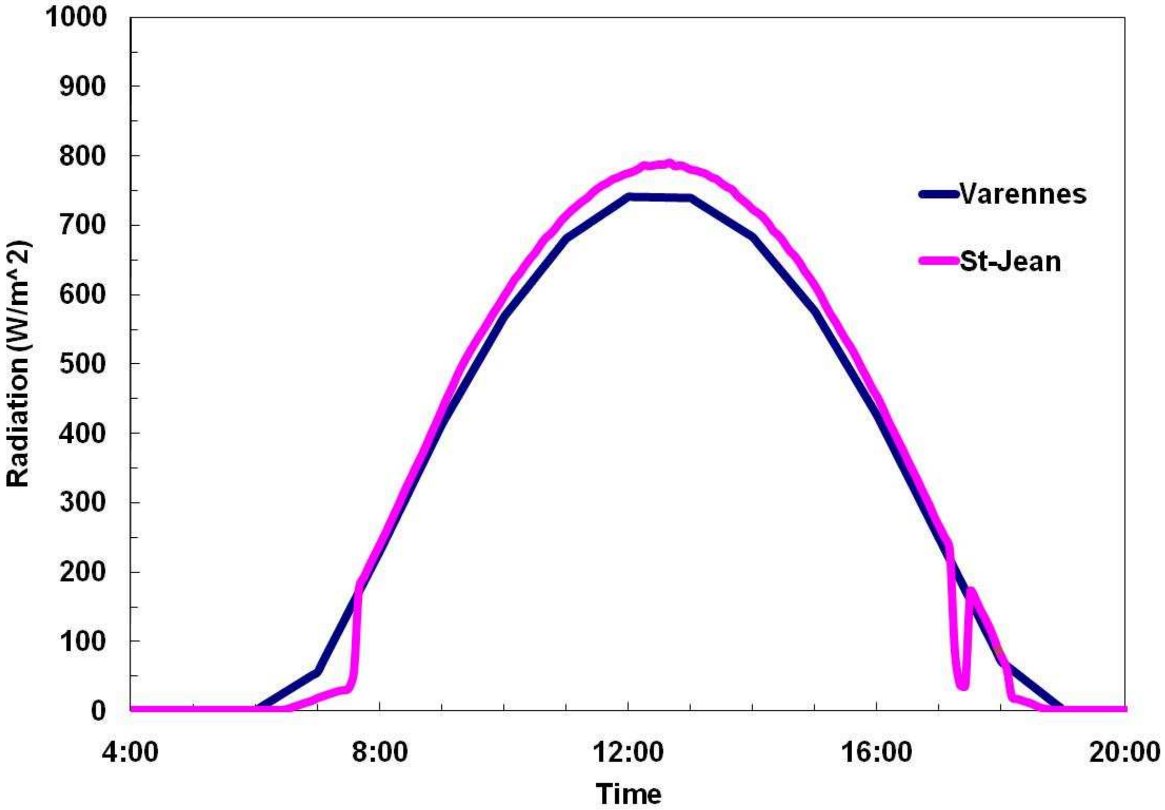

Figure 3.3: Comparison between the horizontal solar radiation values measured at the Varennes weather station of Environment Canada (Latitude 45.7°) and those measured by the horizontal Hobo silicon pyranometer radiation sensor used on the experimental site at St-Jean Baptiste (Latitude 45.5°) on March 17th , 2008,

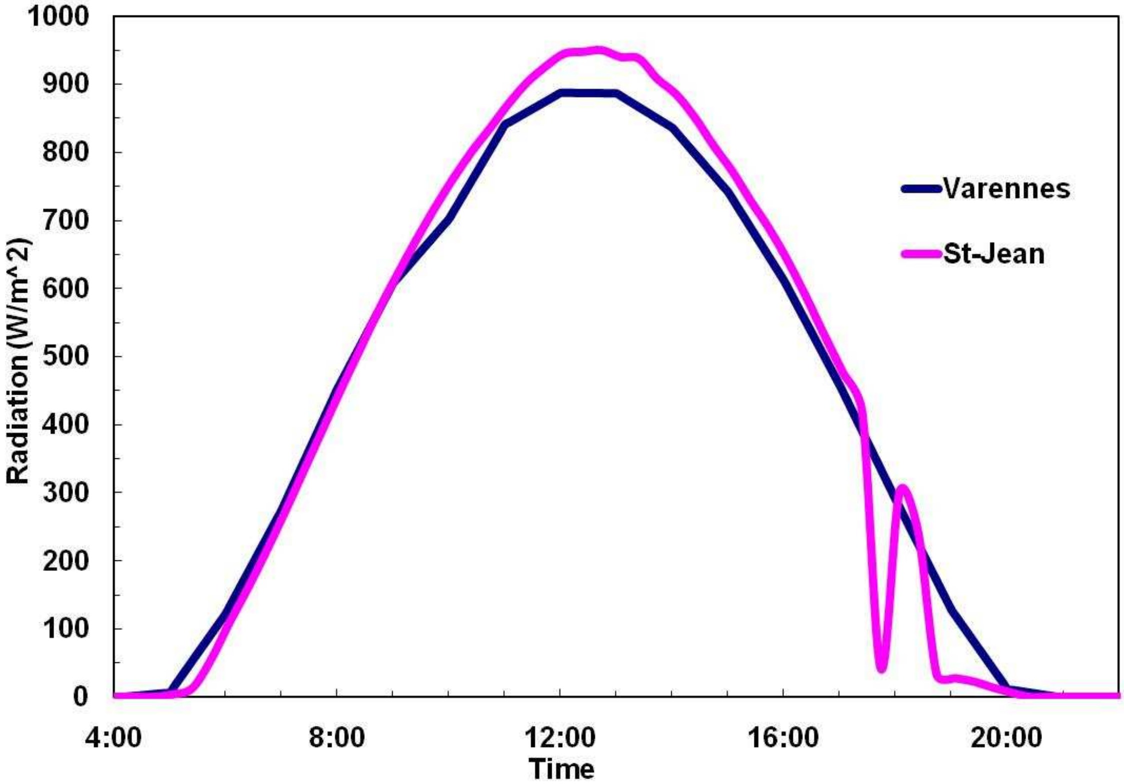

Figure 3.4: Comparison between the horizontal solar radiation values measured at the Varennes weather station of Environment Canada (Latitude 45.7°) and those measured by the horizontal Hobo silicon pyranometer radiation sensor used on the experimental site at St-Jean Baptiste (Latitude 45.5°) on July 22nd, 2007.

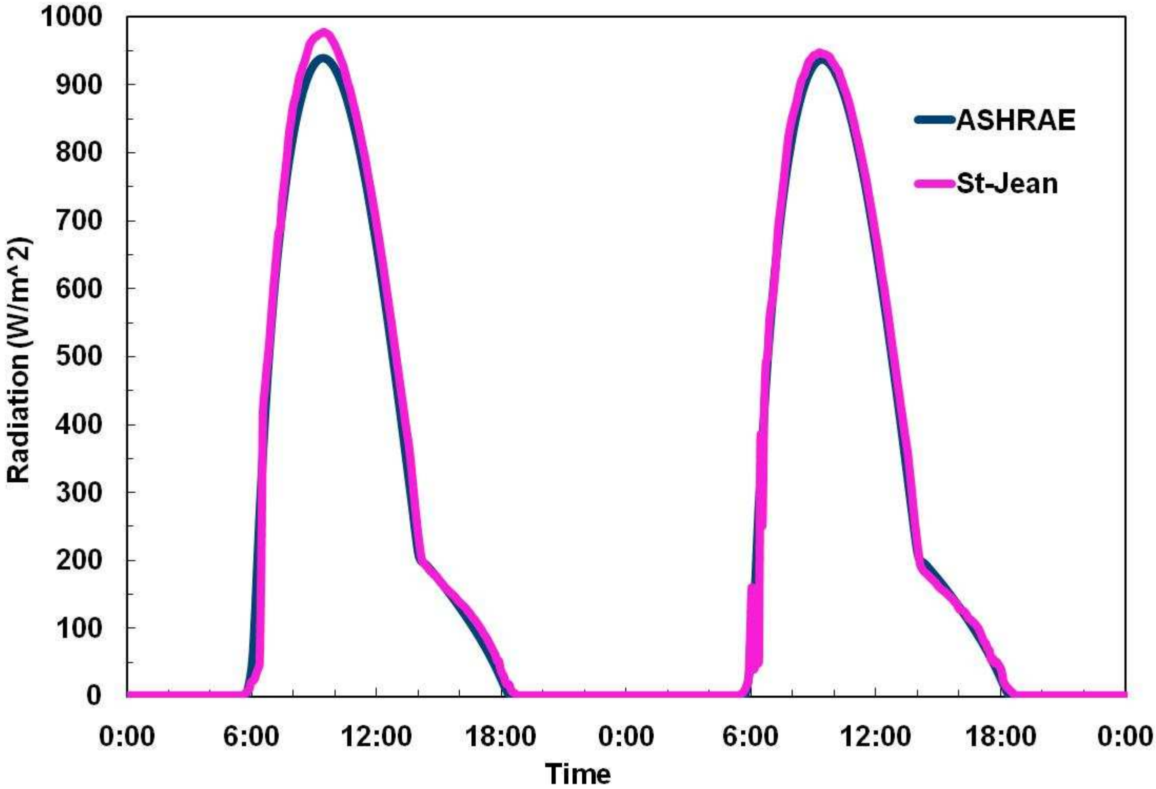

Figure 3.5: Comparison between the vertical absorbed solar radiation measured by the Hobo silicon pyranometer radiation sensors on the experimental site (Latitude 45.5°) and that calculated using Equation (15), with an adjusted ground reflection factor ρ_g to give a corresponding value after 3:00 pm for April 6 and 7, 2008 with a ground reflection factor ρ_g of 0.2.

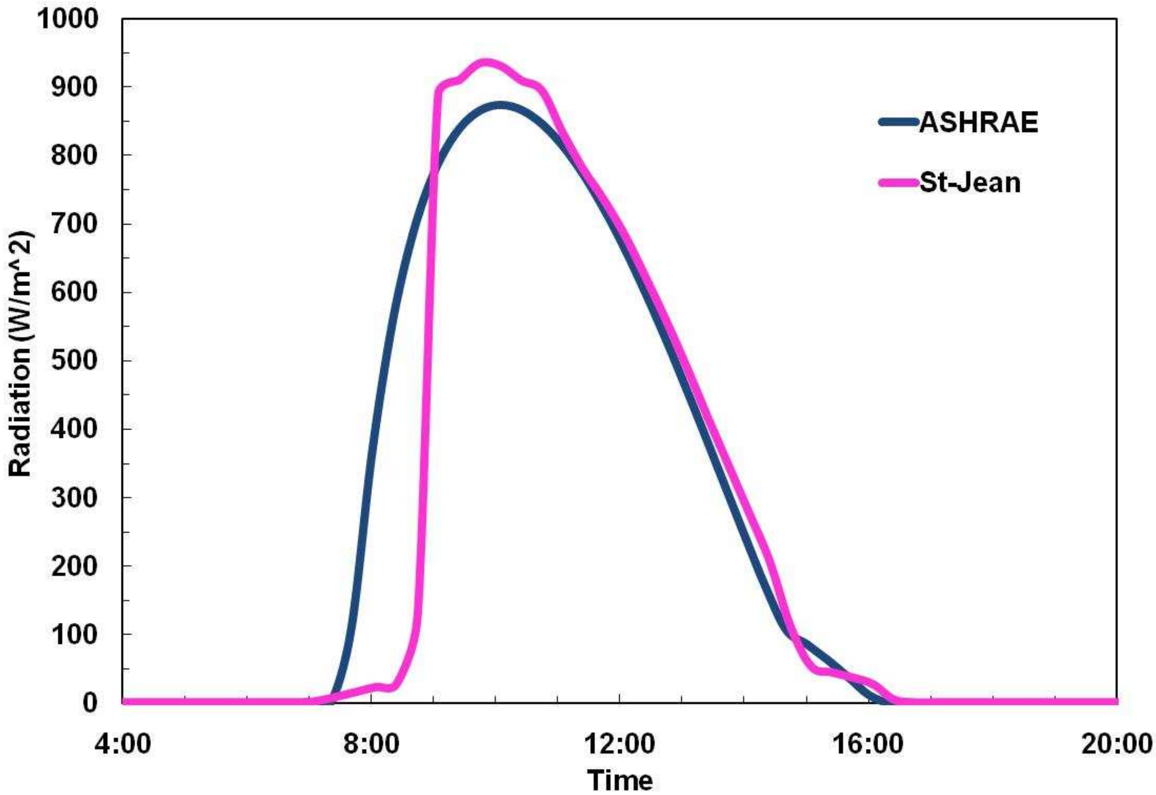

Figure 3.6: Comparison between the vertical absorbed solar radiation measured by the Hobo silicon pyranometer radiation sensors on the experimental site (Latitude 45.5°) and that calculated using Equation (15), with an adjusted ground reflection factor ρ_g to give a corresponding value after 3:00 pm for November 19, 2007 with a ground reflection factor ρ_g of 0.3.

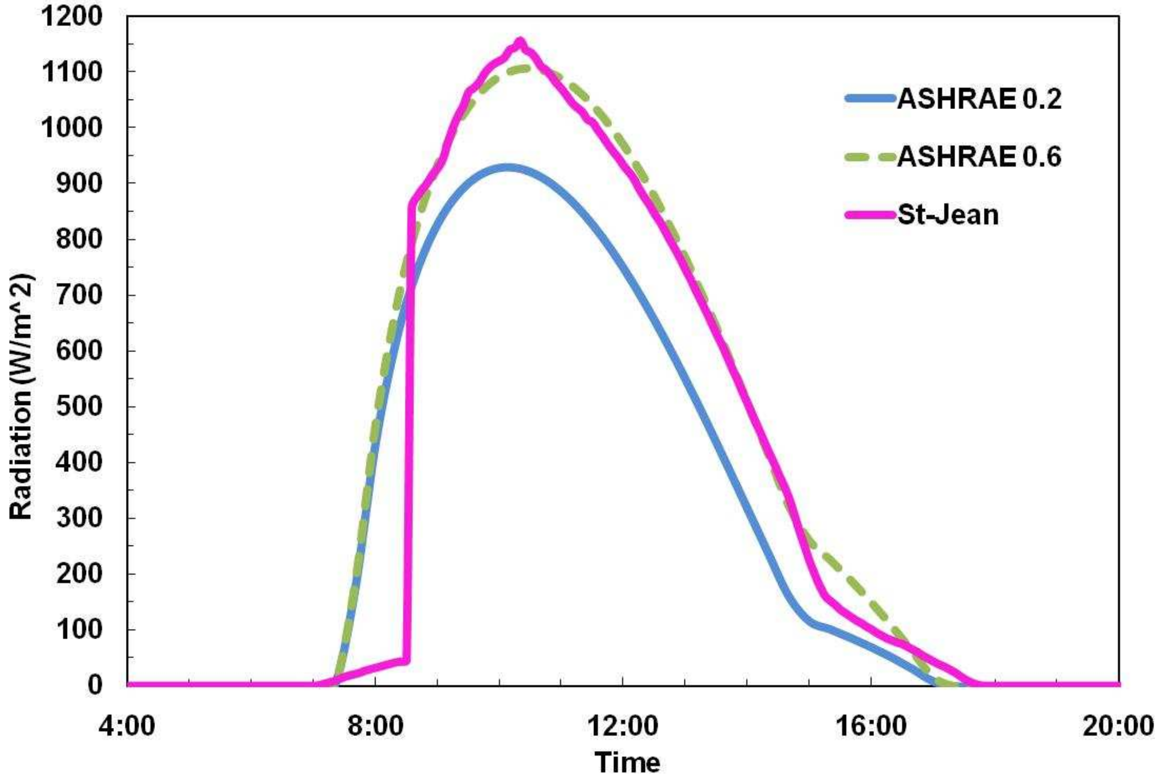

Figure 3.7: Comparison between the vertical absorbed solar radiation measured by the Hobo silicon pyranometer radiation sensors on the experimental site (Latitude 45.5°) and that calculated using Equation (15), with an adjusted ground reflection factor ρ_g to give a corresponding value after 3:00 pm for February 14th, 2009 with a ground reflection factor ρ_g of 0.6.

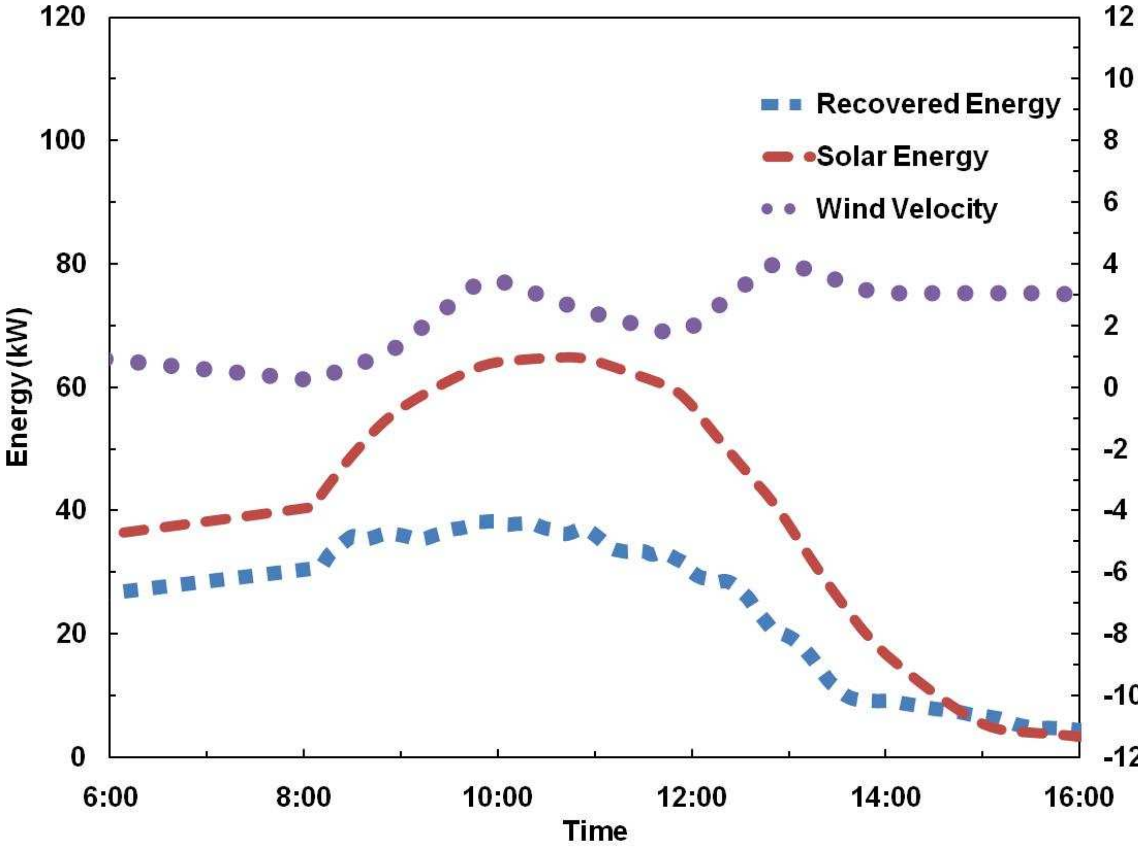

Figure 3.8: Solar pre-heater energy recovery on: March 5th 2009 for an average wind velocity of 2.6 m/s and a heat recovery efficiency was 63%.The heat recovery ∞ and recovery efficiency ε are calculated according to Equations (16) and (17), respectively while the solar energy was measure from the solar radiation sensor multiply by the area of the solar air pre-heater.

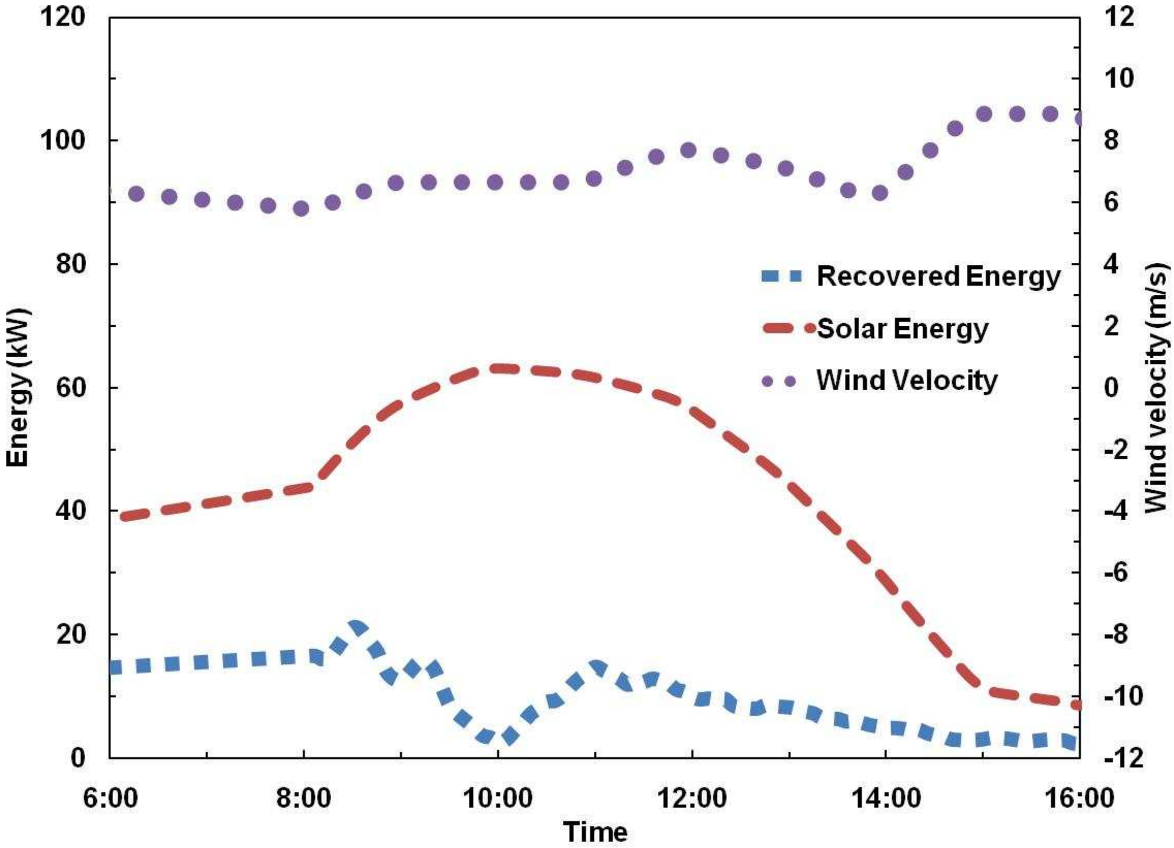

Figure 3.9: Solar pre-heater energy recovery on March 12th, 2009 for an average wind velocity of 7.2 m/s and a heat recovery efficiency was 20%. The heat recovery ∞ and recovery efficiency ε are calculated according to Equations (16) and (17), respectively while the solar energy was measure from the solar radiation sensor multiply by the area of the solar air pre-heater.

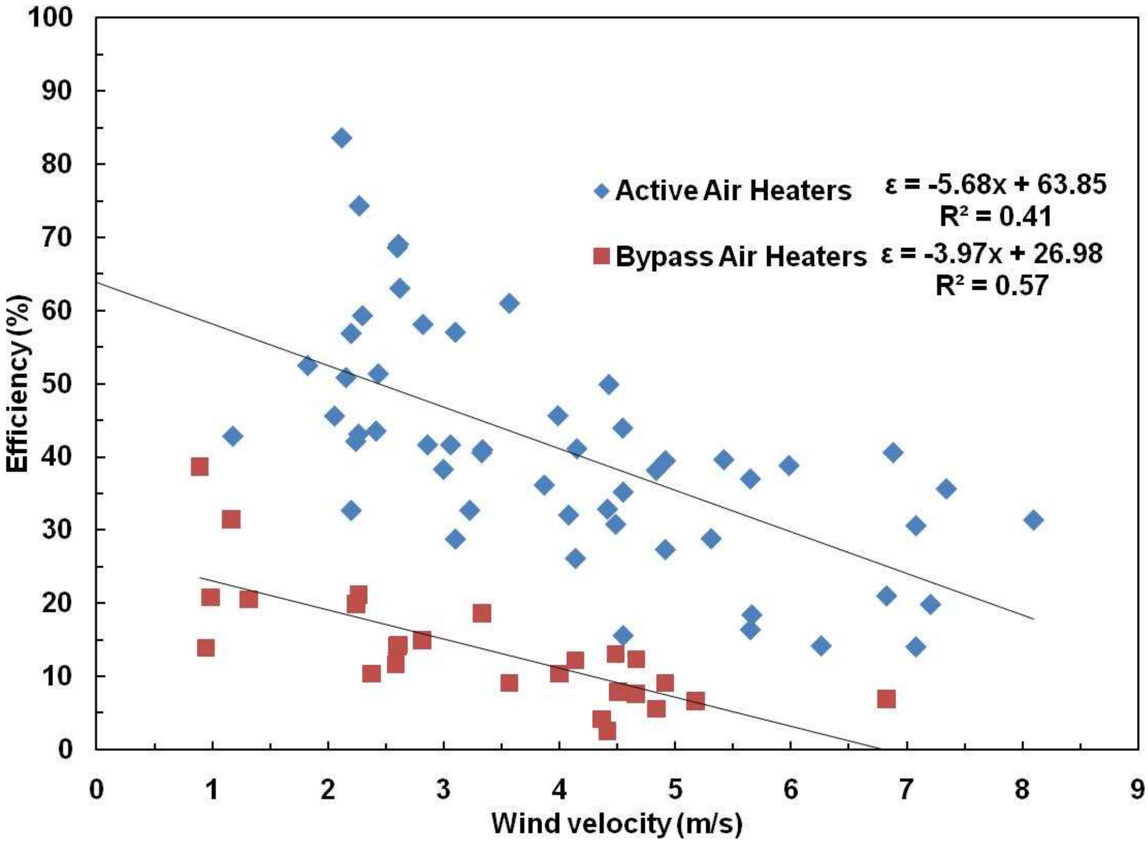

Figure 3.10: Heat recovery efficiency versus wind velocity. Depending on the growth stage of the broilers, the ventilation rate varied between 0.86 and 1.14 m^3/s. The bypass solar pre-heater condition corresponds to opening the bottom panel of the solar air pre-heater frame and allowing fresh air to circulate only on the back surface of the black metal siding before entering the building, and; the active solar wall condition corresponds to forcing the fresh air circulation over the black metal siding, through its perforations, along its back and then into the building. For both regression equations, ε refers to efficiency in% and WS to wind velocity in m/s.

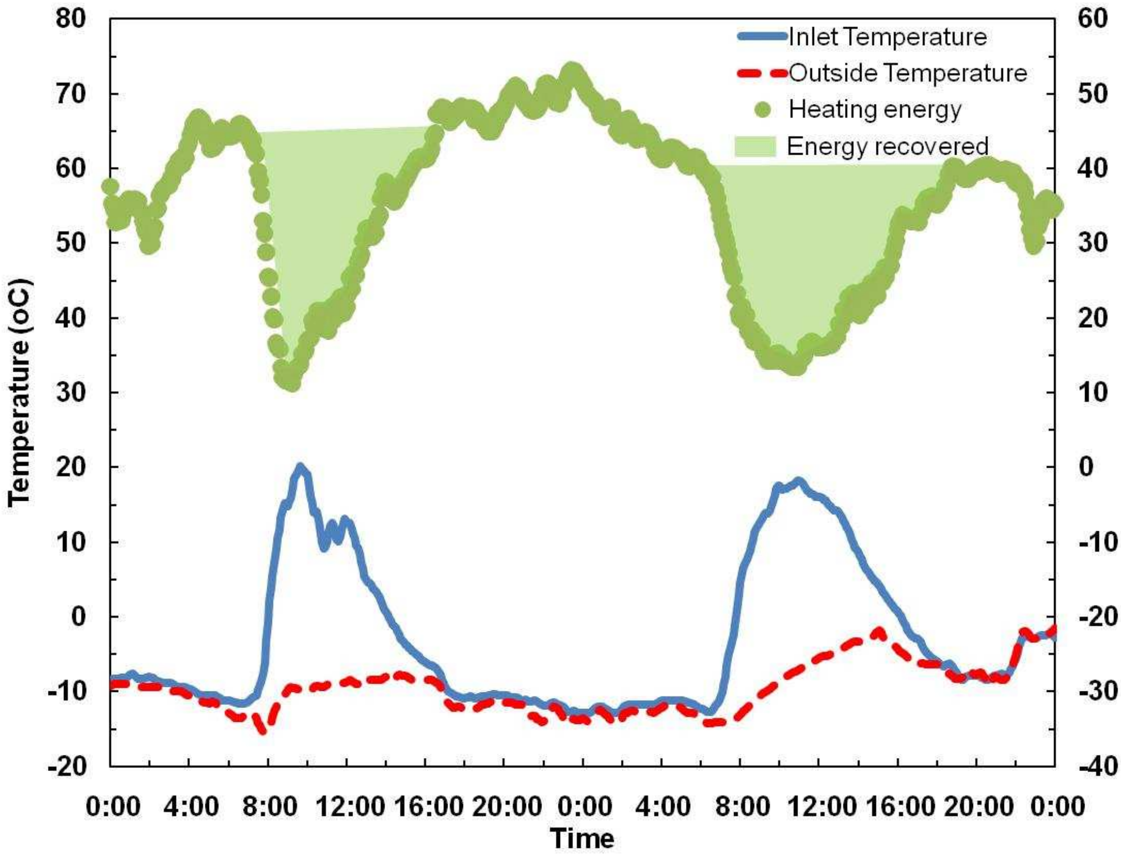

Figure 3.11: Saving in heating load as the solar air pre-heaters recover energy and increase the temperature of the incoming fresh air on February 24th and 25th, 2009. On each 8h day of sunshine respectively, the solar air pre-heaters saved 432 and 540MJ in heating load.

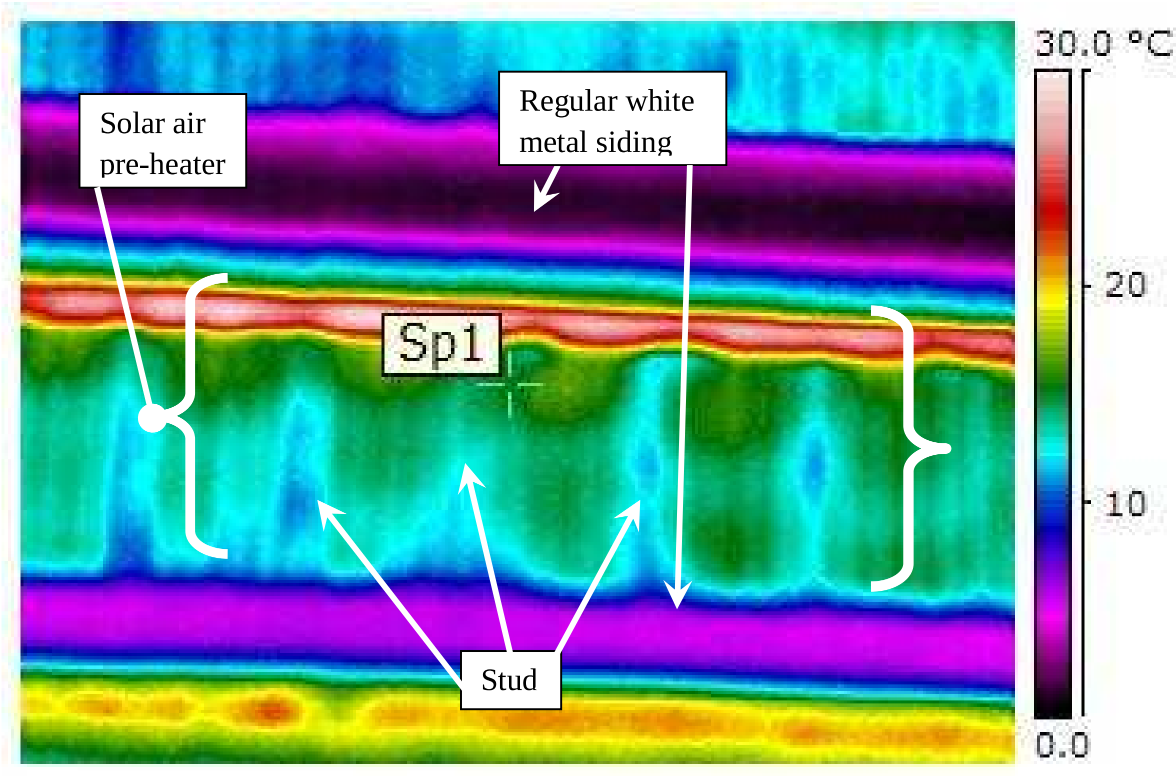

Figure 3.12: Exterior infra-red view of a portion of the solar air pre-heaters. The white metal sheeting covering the barn wall has a temperature below 7^{o}C compared to the ambient exterior temperature at 0^{o}C. The incoming air temperature increases progressively over the surface of the solar air pre-heater before entering the barn.

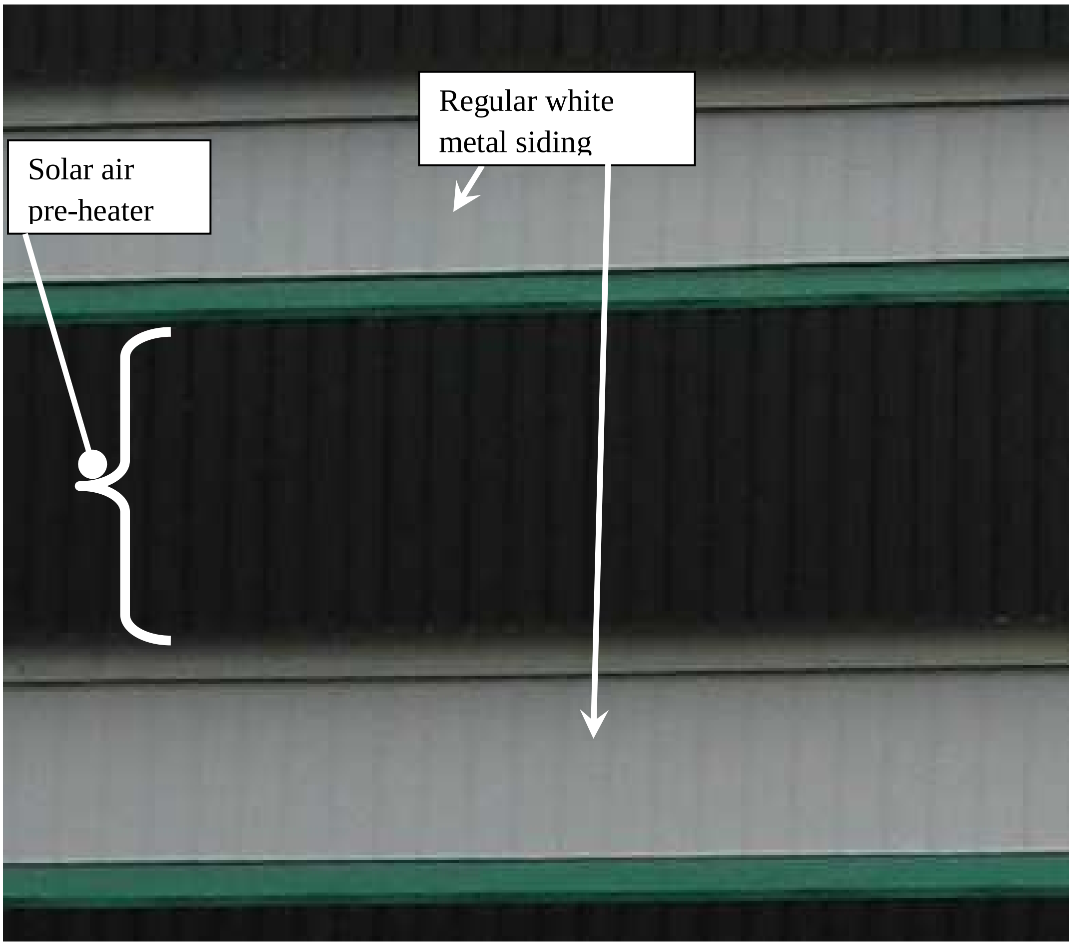

Figure 3.13: The regular view of solar air pre-heater.

Connecting Statement to Chapter 4

Although the agricultural potential and efficiency of solar air pre-heaters can be measured from the energy saved, the agricultural potential can be further demonstrated if there are positive impacts on bird performance. Chapter 4 examines the production of heat by broilers under commercial conditions and the impact of the solar air per-heaters on the ventilation rate and bird performance.

This chapter is drawn from an article prepared for publication in the Journal of Biosystems Engineering. The manuscript was co-authored by Sebastien Cordeau, M.Sc candidate at McGill University and Dr. Suzelle Barrington, Supervisor and Professor at McGill University. The format has been changed to be consistent with this thesis.

Chapter 4: Heat balance for two commercial broiler barns with ventilation air solar pre-heaters

4.1 Introduction

The performance of livestock is influenced by many interacting factors, such as genetics, feeding regime, health management, and housing comfort and environment (Miles et al. 2005). The environmental factors include air quality parameters such as temperature, moisture, particulate matter and gases generally found in concentrations exceeding those in the atmosphere (Seedorf et al. 1998). In livestock barns and based on an approach of heat and gas dilution using fresh exterior air, temperature is used to regulate the ventilation rate (Gates et al. 2001) because thermostats are robust and resistant to contaminants as opposed to relative humidity and gas sensors. Accordingly, parameters other than shelter air temperature are generally controlled by adjusting the minimum ventilation rate as exterior conditions change. Nevertheless, operators are conscious that higher ventilation rates can increase heating costs (Axaopoulos and Panagakis 2003).

Controlling inside air relative humidity and reducing gas levels, such as for NH_3 and CO_2, may have a positive impact on livestock performance especially in temperate climatic zones such as Canada (Perderson and Thomsen 2000; O'Connor et al. 1987). Furthermore, barn air quality can be poorer when the livestock are raised on litter where the degradation of accumulated faeces and urine generates additional moisture, NH_3 and CO_2 (Jeppson 2000). Ambient CO_2 levels depend on ventilation rate, livestock density and mass, heating system operation and floor litter. To reduce heating costs and increase energy conversion efficiency, the fumes produced by the propane or natural gas heaters can be exhausted inside the barn. Such a practice further increases CO_2 levels and imply that higher ventilation rates will not necessarily correct CO_2 levels.

Research has not been conclusive with respect to the effect of high CO_2 levels on broiler chicken performance. Broiler chicks raised for 14 days under CO_2 levels of 3 000 to 9 000 ppm, and thereafter under normal CO_2 levels of 1 000 ppm, demonstrated a growth rate decreasing with CO_2 but an unaffected feed conversion and mortality until the age of 28 days (Olanrewaju et al. 2005). At this point, mortality rate increased from 5.3 to 12.1% mostly as a result of ascities while cumulative growth rate was not affected. A condition leading to the accumulation of ascetic fluid in body cavities, ascities leads to either death or carcass condemnation. (McGovern et al. 2001) reported no difference in ascities incidence for broilers exposed to 6 000 ppm of CO_2 decreased over 6 weeks to 2 500 ppm as compared to 600 ppm of CO_2 increased over 6 weeks to 2 500 ppm.

To lower heating costs, solar air pre-heaters were proposed for fresh ventilation air during the winter (Sokhansanj and Schoenau 1991). Despite high energy costs and issues of greenhouse gas production, few livestock producers are adapting this technology because payback periods have not been justified. The objective of the present research was to conduct a heat balance on two commercial broilers barns located 40 km east of Montreal, Canada, and equipped with solar air pre-heaters over their fresh air inlets. The aim of this heat balance study was to measure bird heat production rate under field conditions, evaluate the impact of solar air pre-heaters on ventilation rate, bird performance and heating load, and identify strategies to reduce winter heating load. The two experimental broiler barns were identically built and instrumented to monitor inlet, inside and outside air conditions, ventilation rate and heating system operating time. The operation of the solar air pre-heaters was alternated between barns to measure the impact on bird performance while reducing barn effects. Broiler performance was monitored by measuring feed conversion, growth rate, mortality and carcass confiscation during slaughtering.

4.2 Materials and methods

4.2.1 Experimental barns and their automated monitoring systems

The two experimental and identically built broiler barns A and B were located in St-Jean-Baptiste, 40 km east of Montreal, Canada, at 45.5° latitude. These barns measured 9.2 m in width and 61 m in length of which 57.9 m was used to house the broilers. Part of a group of 12 parallel broiler barns each built 58 m apart, barns A and B offered three floors, identified as A1, A2 and A3, and B1, B2 and B3, respectively.

Facing the southeast at an angle of 50° from the south, the barn fresh air inlets were equipped with solar air pre-heaters measuring for each floor, 1.47 m in height and 50.1 m in length, for 73.6 m^2 of solar air pre-heater/floor or 221 m^2/barn. The solar air pre-heaters consisted of a wooden box frame built over each fresh air inlet (Figure 4.1). The unprotected facing of black corrugated metal sheeting had small perforations covering 1% of its surface through which fresh air was drawn by the barn ventilation system. Before entering the barn through the inlets, the cold fresh air flowed over the perforated metal sheeting, through the perforation and behind the sheeting (see Chapter 3). The solar air pre-heaters could be bypassed by opening the bottom portion of the wooden box frame.

Both barns were filled in sequence with batches of 7 days old broiler chickens raised for 35 to 45 days, from 0.035 to 2.5 kg in body mass. For any given barn, all three floors were filled and emptied at the same time. During the cold season and once the broilers were freshly introduced into the barns, only two 400 mm fans/floor were operated at a minimum speed of 55% (0.43 m^3/s/fan). The speed of these exhaust fans was increased from 55 to 100% (0.94 m^3/s/fan) over a temperature increment of 1.4°C by an automated controller governed by three thermocouples distributed over the length and in the centre of the room at 0.3 m off the floor. The initial temperature set-point of 32°C was dropped by 0.27°C/day to 24°C. After one to three weeks, a third 400 mm fan was placed in operation and all three fans handled the fresh air ventilation rate until the end of the batch. During the winter period studied, the ventilation rate generally remained at its minimum level of 0.86 and 1.14 m^3/s with two and three 400 mm fans operating at 55% respectively, while the gas heaters were operated regularly.

The experimental barns were instrumented to monitor inside air temperature, relative humidity and CO_2. The inside air temperature was measured at a floor height of 0.3 m (T_1, T_2 and T_3), next to the thermocouples controlling the ventilation system (Figure 4.2) using 8-bit Smart sensors (model HOBO S-THB-M002, Onset Computer Corporation, Pocasset, MA, USA), except for the central temperature sensor (T_2) also measuring air relative humidity using a 12-bit Smart sensor (model HOBO S-THB-M002, Onset Computer Corporation, Pocasset, MA, USA). One more temperature 8-bit Smart sensor (T_4) was installed just before the northeast 400 mm diameter fan in continuous operation. The temperature of the incoming fresh air was measured at two locations inside the air inlets (T_5 and T_6) of each floor (8-bit Smart sensors, model HOBO

S-TMA-M017, Onset Computer Corporation, Pocasset, MA, USA). One CO_2 sensor with a range of 0 to 2500 ppm (Model GMD20, Vaisala Corporation,Vantaa, Finland) was installed in the centre of the second floor of each barn, at a height of 1.5 m. Each floor was heated using two 30 kW natural gas heaters (Figure 4.2). Heat production was monitored using a 5V AC adapter sending a signal to the data logger to register running time. The ventilation rate was monitored by recording the rpm of one 400 mm fan/floor using an electromagnetic converter (Heber et al. 2001). The air flow rate was computed from a correlation obtained using a Balometer (ALNOR EBT721 Balometer, Huntingdon Beech, CA, USA) during which the volumetric air displacement of all 400 mm fans was measured at an rpm varying from 55 to 100% (Figure 4.3). A Hobo data logger (Onset Computer Corporation, Pocasset, MA, USA) recorded all readings every 5 minutes.

Installed on a tower 3.0 m high and located in a grassed area mid way between the two broiler barns, a weather station recorded the ambient climatic conditions, namely wind velocity and direction, ambient air temperature, barometric pressure and relative humidity, and absorbed radiation. Two solar radiation sensors (Hobo Silicon Pyranometer Smart Sensor, Onset Computer Corporation, Pocasset, MA USA) were placed in a horizontal and vertical position, respectively, to measure the horizontally absorbed radiation and the radiation adsorbed by the solar air pre-heaters. The vertical radiation sensor was placed parallel to the solar air pre-heaters using a compass. By comparing values with those of the Varennes Environment Canada weather station located 30 km northwest, the maximum reading error of the radiation sensors, including the effect of atmospheric water vapour, was found to be within 7% (See Chapter 3). A Hobo data logger (Onset Computer Corporation, Pocasset, MA, USA) recorded all weather data readings every 5 minutes.

4.2.2 Methodology

Besides heat balance and energy conservation, the objective of the project consisted in monitoring bird performance with and without the operation of the solar air pre-heaters. Covering the period of September 2007 to April 2009, monitoring sessions started with the reception of 7 day old birds and ended when these were fully grown, in an all-in all-out fashion. The faeces and urine of the birds were accumulated throughout the growing period on 50 mm of pine shavings. For each batch, one barn was ventilated using the solar air pre-heaters while for the second barn, the solar air pre-heaters were by-passed by opening the bottom door of the wooden box frames (Figure 4.1). The operation of the solar air pre-heaters was alternated between barns A and B to minimize barn effect. The bird batches were identified by barn, floor and sequence: for example, batch A2-10 was the 10^{th} batch raised on the floor 2 of barn A.

While raising the bird batches from 0.035 to 2.5 kg, the following parameters were monitored: inside air temperature at three locations and relative humidity at one location at a height of 0.3 m on all floors and CO_2 at a height of 1.5 m on floor 2 only; fresh air ventilation rate from the rpm of one 400 mm fan/floor; air temperature at two locations in the inlets on each floor, and; external air conditions, and vertical and horizontal radiation using a weather station half way between barns A and B. Between bird batches, the acquired data was downloaded and the acquisition system components were inspected and maintained. The recorded data was verified against that registered by the barn automated ventilation control system. To further verify the performance of the ventilation system and that of the solar air pre-heaters, infra-red pictures were taken inside barn B on February 18th, 2009.

For marketing purposes, barns A and B were filled in sequence and bird batches between barns were raised under slightly different climatic conditions. In September 2007, batches were introduced in barns A and B a few days apart, but by January 2009 batches were introduced 3 weeks apart. Furthermore, between batches, the type of bird varied from females to males and, for the males, from a regular to a vegetable fat diet. These management differences added variability in bird performance.

For each batch, the sensible and latent heat production rate of the birds was calculated using the acquired data. The sensible heat produced by *N* birds/floor weighing *m* kg in body mass was calculated as equal to that lost by the ventilation system and the barn shell less the heat supplied by the heaters:

$$S_{ec} = [Q \times \rho \times (T_o - T_i) \times C_p] + [\Sigma\, A_i / R_i \times (T - T_e)] - H$$

(1)

where S_{ec} is the calculated sensible heat production rate in kW for *N* birds weighing *m* kg, Q is the ventilation rate in m^3/s, ρ is the density of the inside air at the exhaust fan in kg/m^3, T_i is the average temperature (sensors T_5 and T_6) of the air at the inlet inside the barn in °C, T_o is the temperature of the air inside the barn at the exhaust fan (sensor T_4)

in °C, C_p is the specific heat of air of 1.006 kJ/kg dry air/°C, A_i is a shelter surface in m^2 associated with an insulation value R_i in m^2°C /kW, T is the average temperature of the inside air (sensors T_1, T_2 and T_3) in °C, T_e is the temperature of the outside air in °C, and H is the heating rate of natural gas heater in kW.

The latent heat produced by N birds/floor weighing m kg was equated to that lost by the ventilation system, assuming the barn shell to be relatively impermeable to moisture, less that produced by the natural gas heaters:

$$S_{lc} = [Q \times \rho \times (W - W_e) \times h_{fg}] - H_l$$

(2)

where S_{lc} is the calculated latent heat production rate in kW for N birds weighing m kg, W is the moisture ratio of the air inside the barn computed from the air temperature at the fans (sensor T_4) and air relative humidity at a height of 0.3 m (sensor T_2) in kg/kg of dry air, W_e is the moisture ratio of the exterior air computed from the exterior air temperature and relative humidity in kg/kg dry air, h_{fg} is the heat of vaporization of water in kJ/kg of dry air and H_l is the heater latent heat production rate in kW. Infiltration rate was considered negligible in Equations (1) and (2). Total bird heat production rate S_{tc} was the sum of the sensible and latent heat.

Bird performance was monitored by keeping track of the feed consumed per batch and measuring the mass of 100 birds every week. Bird mortality was recorded on a daily basis as birds were found dead on the floors. At slaughtering, bird confiscation was also noted. During the first year, the floor litter was sampled at nine locations on each floor and analyzed for moisture content by drying for 24 h at 103°C. Because no difference was observed in litter moisture content between barns and floors, this monitoring was not repeated during the second year.

4.2.3 Statistical analysis

Standard deviations and regression equations for heat production rate over time were computed using Excel (Microsoft Office 2007, Seattle, WA, USA). As calculated using Equations (1) and (2), the sensible, latent and total heat production rates, S_{ec}, S_{lc} and S_{tc}, were correlated with time through regression equations. The y-intercept obtained from such regressions was used to estimate the corrected and more realistic rates S_e, S_l, S_t, accounting for effects of inside air stratification on conductive heat transfer between floors and wind on fan air flow rate.

4.3. Results and Discussion

4.3.1 Broiler sensible, latent and total heat production rate

For barn A and the 10th batch of 6 500 birds/floor raised simultaneously under the same outside and inside conditions, Figure 4.4 illustrates the calculated sensible heat production S_{ec} which on floors 2 and 3, is 20 kW higher than that of floor 1 and that reported of 3 kW (Hellickson and Walker 1983). To explain this calculated difference between floors, infra-red pictures were taken inside floor B1 on February 18th, 2009

(Figure 4.6) in the absence of broilers but with the gas heater and two 400 mm fans in operation and under an outside temperature of 0°C. The gas heater created air temperatures of 42 and 32°C at the ceiling and floor on the left hand side of the room. On the opposite side, air at the ceiling and floor was at 38 and 28°C and as low as 25°C against the walls likely because of less insulation. Such stratification in air temperature with warmer conditions at the ceiling demonstrates the upward convective heat movement likely enhanced in the presence of birds producing additional heat. Since floor 1 looses heat only while floors 2 and 3 gain and loose heat, the calculated heat loss by conduction needs correction solely for floor 1. With a temperature differential of 10°C, the ceiling conduction heat loss of 20 kW corresponds to a reasonable insulation value of 270 m^2°C/kW for a 16 mm plywood floor, wetted while washed a few days earlier, and covered with an uneven and damp (15% moisture) 50 mm layer of pine shavings (ASHRAE 2009).

Accordingly, after correcting for heat transfer through the ceilings, all three floors for batch 10 of barn A show a calculated broiler sensible heat production of 20 kW above that expected. This additional sensible heat was found to be common to all floors and both barns, indicating a common discrepancy resulting either from overestimating heat lost by the ventilation system or underestimating heat production by the gas heaters. The heat produced by the gas heaters corresponded to that recorded by the barn automated ventilation control system and gas consumption, leaving the ventilation rate as a possible source of error. Among the three 400 mm fans operated during the experimental period, only that on the northeast side was monitored for air flow rate and exhaust temperature. Because of the dominant westerly winds and the experimental barns protected inside a series of 10 others, the monitored northeast side fan likely exhausted a higher rate of air also at a higher temperature. Effectively and between batches, higher wind speeds and lower outside temperatures were found to increase the y-intercept value up to 40 kW, as obtained from the regression of bird sensible heat production rate over time and with batches. In conclusion, a more accurate ventilation air flow rate requires the monitoring of all fans in operation, rather than just one/floor.

To correct the calculated sensible heat values produced by the birds, a regression equation was obtained to define S_{ec} against time, using the data from all batches of barns A and B. The y-intercept was then used to lower S_{ec} and compute S_e (kW/kg bird mass) as a function of bird age (Figure 4.5). Accordingly, when weighing 1.0 kg, the broilers produced 4.5 W/kg of sensible heat with a feed conversion rate of 1.80 kg of feed/kg of bird mass. The measured sensible heat production rate for 1.0 kg broilers (m_1) was found to be similar to that of 5.2 W/kg observed in the laboratory by (CIGR 1984):

$$S_{el} = S_t \times (0.8 - 1.85 \times 10^{-7} \times (T + 10)^{4}) \qquad (3)$$

and of 4.3 W/kg by (Chwalibog et al. 1985) for broilers kept on 50 to 100 mm of wood shavings at 24°C:

$$S_{el} = 9.21 \times m_1^{0.79} - 4.91 \times m_1^{0.68} \qquad (4)$$

For broilers with a similar feed conversion rate of 1.63 to 1.65 kg of feed/kg of bird mass, Perderson and Thomsen (2000) observed that sensible heat production rate was reduced by 17% because of water evaporated from troughs and bedding.

In parallel, using Equation (2), Figure 4.7 illustrates the latent heat produced by the same 10^{th} bird batches in barn A. Although the values are similar between floors, the initial latent heat production of 20 kW is much higher than that reported of 0.5 kW (Hellickson and Walker 1983). The calculation error results from the hypothesis that the outlet moisture ratio can be calculated from the air temperature at the fan and the air relative humidity at 0.3 m off the floor. When using the air temperature and relative humidity at 0.3 m off the floor, the calculated initial broiler latent heat production drops by 10 kW, where the remaining 9.5 kW difference can be attributed to the variable fan air flow rate and the higher concentration of air water vapour close to the floor as produced by the birds and water troughs. Accordingly, latent heat production requires the monitoring of both temperature and relative humidity of all exhaust fans. Furthermore, because sensible heat values calculated from Equation (1) change with floor while latent heat values from Equation (2) are similar, a limited within-barn convective effect can be concluded.

Using once more the y-intercept obtained from a regression between the calculated latent heat production rate and time for all batches raised in barns A and B, Figure 4.8 illustrates the corrected values giving 4.25 W/kg for birds weighing 1.0 kg. This value corresponds to that observed in the laboratory of 4.65 W/kg by (CIGR 1984) and 4.53 W/kg (Chwalibog et al. 1985).

Representing typical values obtained by adding S_e and S_l, corrected broiler total heat production rates S_t for all bird batches are illustrated in Figure 4.9. The total heat production for a bird weighing 1 kg (m_1 = 1 kg) is estimated at 8.45 W/kg, which corresponds to that observed under laboratory conditions by (CIGR 1984):

$$S_{tl} = 10 \times m_1^{0.75} \times \{4 \times 10^{-5} \times (20-T)^3 + 1\} \qquad (5)$$

and by (Chwalibog et al. 1985) for broilers kept on 50 to 100 mm of wood shavings:

$$S_{tl} = 10.5 \times m_1^{0.79} \quad \text{at } T = 20°\text{C} \qquad (6a)$$

$$S_{tl} = 9.21 \times m_1^{0.79} \quad \text{at } T = 24°\text{C} \qquad (6b)$$

$$S_{tl} = 8.09 \times m_1^{0.75} \quad \text{at } T = 28°\text{C} \qquad (6c)$$

At 24°C, Equations 5 and 6b give respectively a total heat production of 9.97 and 9.21 W for a bird weighing 1.0 kg.

Accordingly, and once corrected for effects of air temperature stratification and variable fan air flow rate, the measured commercial broiler heat production rates correspond to those obtained under laboratory conditions. Air temperature stratification resulted in the transfer of 20 to 40 kW of energy during the cold season between floors. When computing the total gas heater operation time, that of floor 1 generated 25% more heat as compared to floors 2 and 3, indicating that inside air stratification can have an important impact on heat losses.

4.3.2 Impact of solar air pre-heaters on ventilation rate and bird performance

The primary objective of the solar air pre-heaters of reducing barn heating cost is illustrated in Figure 4.10 for two sunny days of February 2009 where 432 and 540 MJ/floor of heating energy was recovered during 8 h of sunshine. The energy recovered was calculated from the product of the air flow rate and the increase in air temperature between that outside and inside the inlets. However, some of the recovered energy was lost every time the solar air pre-heaters quickly increased the inlet air temperature by more than 10°C (Figure 4.11). On February 25th for example, the calculated bird total heat production rate S_{tc}, was observed to drop by 40 kW on floor A3. This phenomenon was attributed to the higher buoyancy of the air at the inlet and its short circuited path towards the fans. In parallel, an accumulation of heat within the barns was detected through higher temperatures at 0.3 m off the floor, which was high enough on occasions to increased the ventilation rate.

On average, based on the number of days during which inlet air temperature resulted in a lower S_{tc} value, approximately 15% of the total energy recovered by the solar air pre-heaters of 180 kW-h of energy/m^2 was lost by ventilation air short circuiting between November 2008 and March 2009. Once more, better inside air mixing could prevent this heat loss.

A second objective of the solar air pre-heaters was to increase the ventilation rate and improve inside air quality and bird performance. Ventilation rates above the minimum occurred especially in March as a result of warmer inlet air temperatures produced by the solar air pre-heaters (Figure 4.12). A ventilation rate above the minimum resulted from a combination of factors eliminating gas heater operation, such as warmer outside temperatures, greater recovery of solar energy and higher broiler heat production as birds gained body mass. For batches 9 and 10 raised in barn A, from December 4th 2008 to January 11th 2009, and from January 30th to March 11th 2009, ventilation rates exceeded the minimum during 6 and 7 days, respectively, whereas in barn B for batch 11, from February 18th to April 1st, 2009, ventilation rate exceeded the minimum during 11 days. In total, the solar air pre-heaters produced higher ventilation rates during 20% of the daytime period from November 2008 to March 2009. Unprotected, the experimental solar air pre-heaters were limited in surface area (See chapter 3 2010) to minimize wind effect against air displacement created by the ventilation rate. If these were protected to double their surface area, higher ventilation rates would occur during 40% of the daytime period.

Even if the solar air pre-heaters were able to increase the ventilation rate during 20% of the daytime period, no apparent effect was observed in terms of bird performance (Table 4.2 and 4.3). Levels of CO_2 remained above 2 500 ppm during most of the monitoring period for both barns A and B, whether the solar air pre-heaters were used or by-passed, because the gas heaters released their exhaust inside the rooms to conserve energy. Floor litter moisture content was similar among barns and between floors, with and without the solar air pre-heater effect, having no influence on feet disease and bird performance. The lack of solar air pre-heater effect on bird performance also resulted from the short 40 day stay of the birds inside the rooms, besides the sporadic increase in ventilation rate above its minimum. Further testing is needed to measure the impact on bird performance of reducing heat losses from air temperature stratification and of increasing the ventilation rate by doubling solar air pre-heater surface.

4.4 Conclusion

The objective of this project was to conduct a heat balance on two commercial broiler barns to measure bird heat production under field conditions, to evaluate the impact of ventilation air solar pre-heaters on heat load and bird performance, and to suggest strategies to reduce winter heating load.

The data collected showed that:

i) the heat produced by the broilers in commercial barns corresponded to that measured under laboratory conditions;
ii) air temperature stratification was a main source of heat loss (25%) and needs to be corrected using ventilation systems capable of mixing the inside air;
iii) ventilation air solar pre-heaters can contribute to reducing heating load during the winter in temperate climatic zones but their performance can be improved by limiting air short circuiting towards the fans;
iv) ventilation air solar pre-heaters may have an impact on livestock performance but their surface area or energy recovery must be high enough to regularly increase the ventilation rate. In this project and from November 2008 to March of 2009, a ratio between barn floor area and solar air pre-heater surface of 3:1 was required to increase the daytime ventilation rate one day out of two.

4.5 References

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Table 4.1: Nomenclature

A_i is a shelter surface in m^2 associated with an insulation value R_i in m^2/kW-°C.

C_p is the specific heat of air of 1.006 kJ/kg dry air/°C.

H is the heater rate of heat production in kW.

h_{fg} is the heat of vaporization of water in kJ/kg of dry air.

H_l is the heater latent heat production rate in kW

m is the mass of each bird.

m_1 is the unit mass of 1 kg for broilers.

N is the number of birds on the floor.

Q is the ventilation rate in m^3/s.

R_i is the insulation value of surface A_i in m^2/kW-°C.

S_e is the corrected sensible heat production rate in W/kg bird mass.

S_{ec} is the calculated sensible heat production rate in kW.

S_{el} is the reported laboratory sensible heat production in W.

S_l is the corrected latent heat production rate in W/kg bird mass.

S_{lc} is the calculated latent heat production rate in kW.

S_{ll} is the reported laboratory latent heat production in W.

S_t is the corrected total heat production in W/kg bird mass.

S_{tc} is the calculated total heat production rate in kW.

S_{tl} is the reported laboratory total heat production in W.

T is the average temperature of the inside air in °C.

T_e is the temperature of the outside air in °C.

T_i is the temperature of the air at the inlet inside the barn in °C

T_o is the temperature of the air inside the barn at the exhaust fan in °C.

W is the air moisture ratio inside the barn in kg/kg of dry air.

W_e is the air moisture ratio outside in kg/kg dry air.

ρ is the air density in kg/m^3.

Table 4.2: Bird performance with energy recovery from solar air pre-heaters

Bird type	Performance		
	Death (number)	Feed conversion (kg feed/kg weight gain)	Confiscation at slaughter house (%)
male	401	1.81	2.00
male	404	1.78	2.11
male	479	1.79	2.45
male	270	1.72	3.50
male	594	1.79	2.90
male	621	1.90	3.38
Mean	462	1.80	2.72
Standard deviation	(132)	(0.06)	(0.64)

Table 4.3: Bird performance without energy recovery from solar air pre-heaters

Bird type	Performance		
	Death (number)	Feed conversion (kg feed/kg weight gain)	Confiscation at slaughter house (%)
female	404	1.82	1.32
male	261	1.73	2.36
female	831	1.81	1.93
male	551	1.76	2.97
Male on vegetable fat diet	980	1.81	2.26
male	742	1.83	3.03
Mean	628	1.79	2.31
Standard deviation	(272)	(0.04)	(0.65)

Figure 4.1: Solar air pre-heaters over the fresh air inlets and bottom door used for their bypass during the warm seasons.

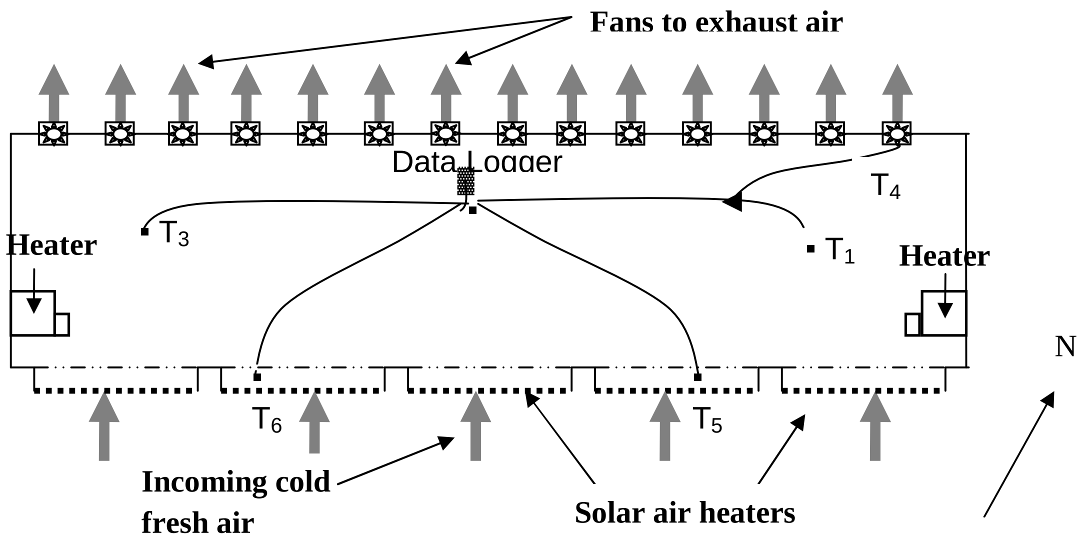

Figure 4.2: Instrumentation of experimental barns where: T_1, T_2, T_3 are air temperature sensors installed inside the building at 0.3 m off the floor; T_4 measures the outgoing air temperature at the exhaust fan in continuous operation, and; T_5 and T_6 measure the temperature of the incoming fresh air at the inlet after the solar air pre-heaters.

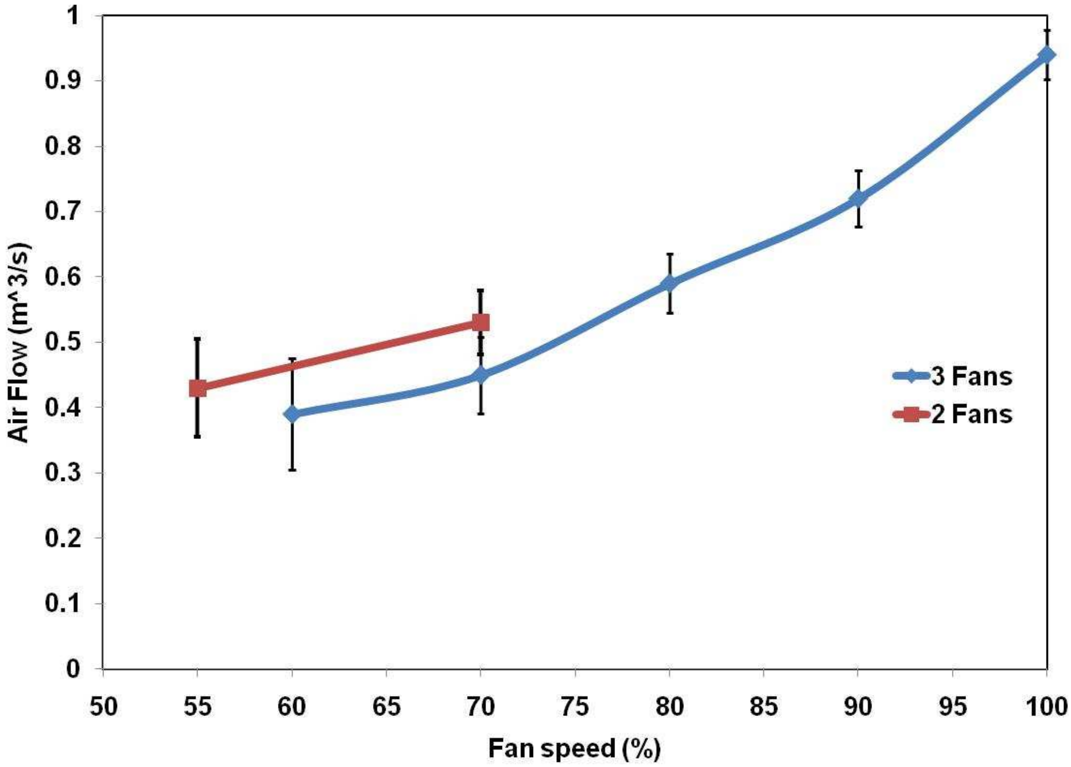

Figure 4.3: Average ventilation rate measured for the nine 400 mm inside diameter fans of the experimental building A as a function of fan speed (coefficient of variation in air flow rate among fans of 15%).

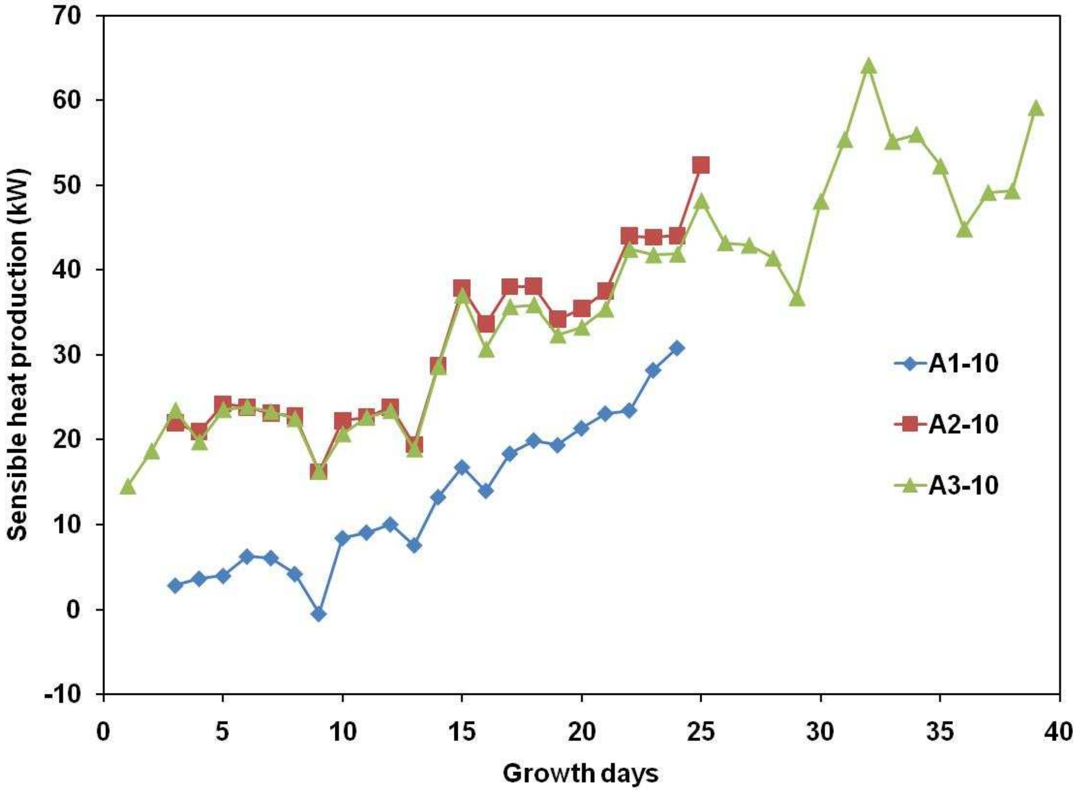

Figure 4.4: Total calculated sensible heat production S_{ec} for batch A1-10, A2-10 and A3-10 (floors 1, 2 and 3, respectively), from January 30th to March 7th 2009. The calculated sensible heat production is higher for floors 2 and 3 because of air temperature stratification inside the rooms leading to heat conduction towards the upper floor.

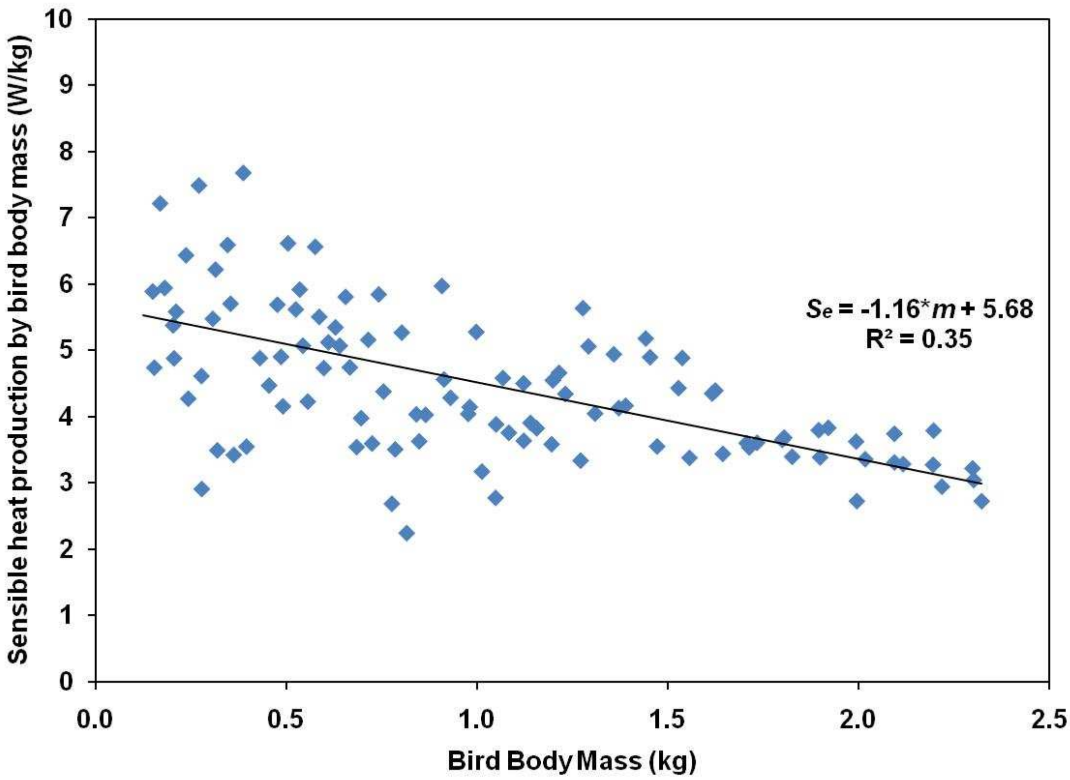

Figure 4.5: Corrected sensible heat production (S_e) per kg of bird body mass (m) averaged for batches raised during the winter of 2008-2009. The calculated heat production was corrected to remove the heat conducted between floors.

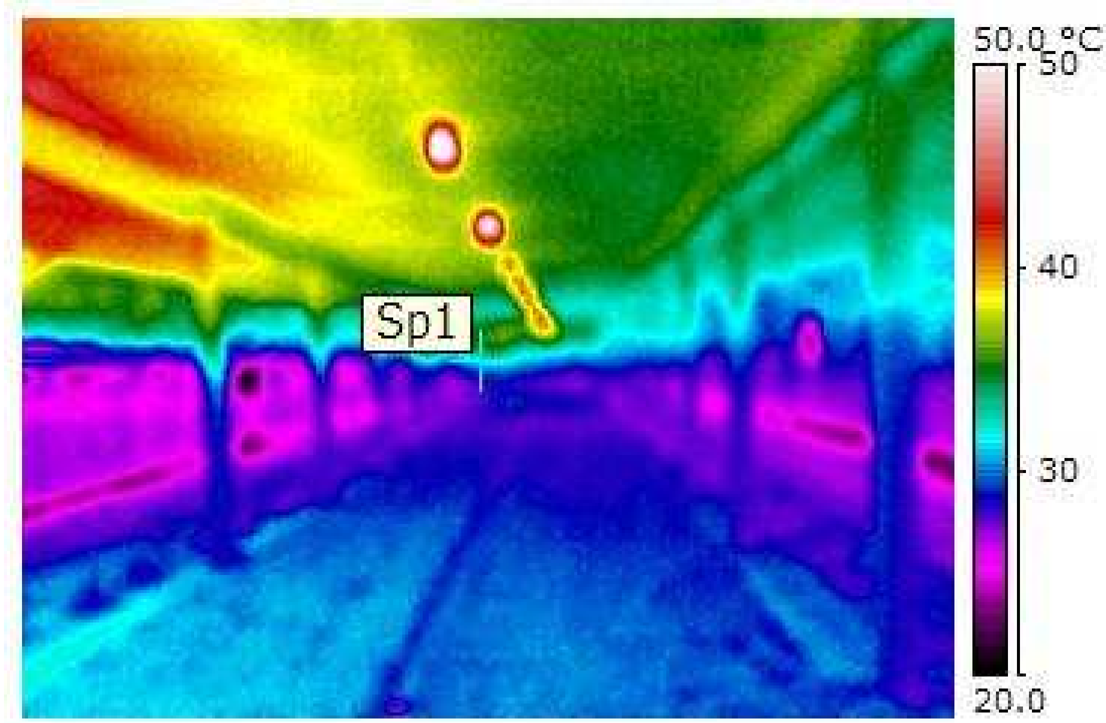

Figure 4.6: Infra-red view of the floor 1, barn B, on February 18th, 2009, in the absence of birds but with the solar air pre-heaters and the ventilation system in operation and an outside air temperature of 0°C. The ceiling air temperature on the left results from the gas heater and reaches 42°C while that on the right side is at 38°C. The floor temperature ranges from 28 to 32°C, with higher temperatures under the gas heaters. This temperature difference indicates air stratification resulting in conductive heat exchange between floors. The solar air pre-heaters located on the left side are associated with wall temperatures of 20-25°C while for the fans on the right (pink circle) the wall is warmer at 28°C.

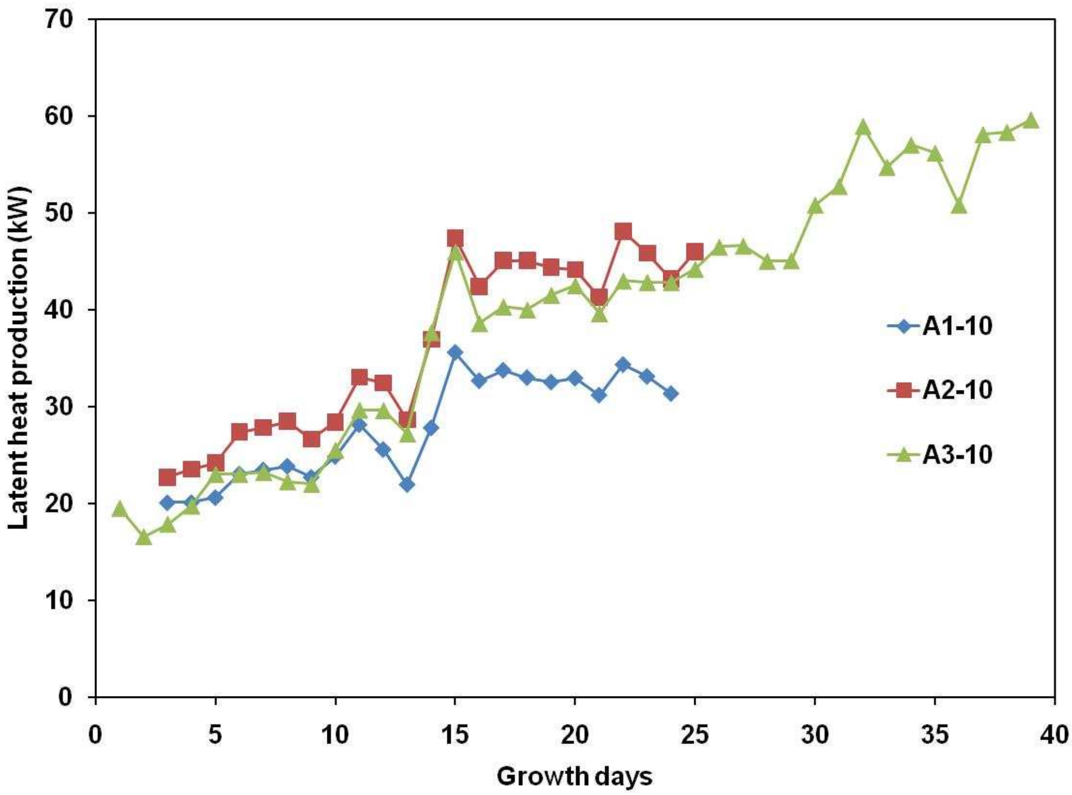

Figure 4.7: Total calculated latent heat production (S_{lc}) for batches A1-10, A2-10 and A3-10 raised on the floors 1, 2 and 3, respectively, from January 30th to March 7th 2009. The latent heat production is similar between floors, indicating limited convective air transfer between floors. Nevertheless, the high initial level of latent heat production common to all three floors indicates that the vented air had a lower moisture ratio than that used in the calculations as a result of air stratification.

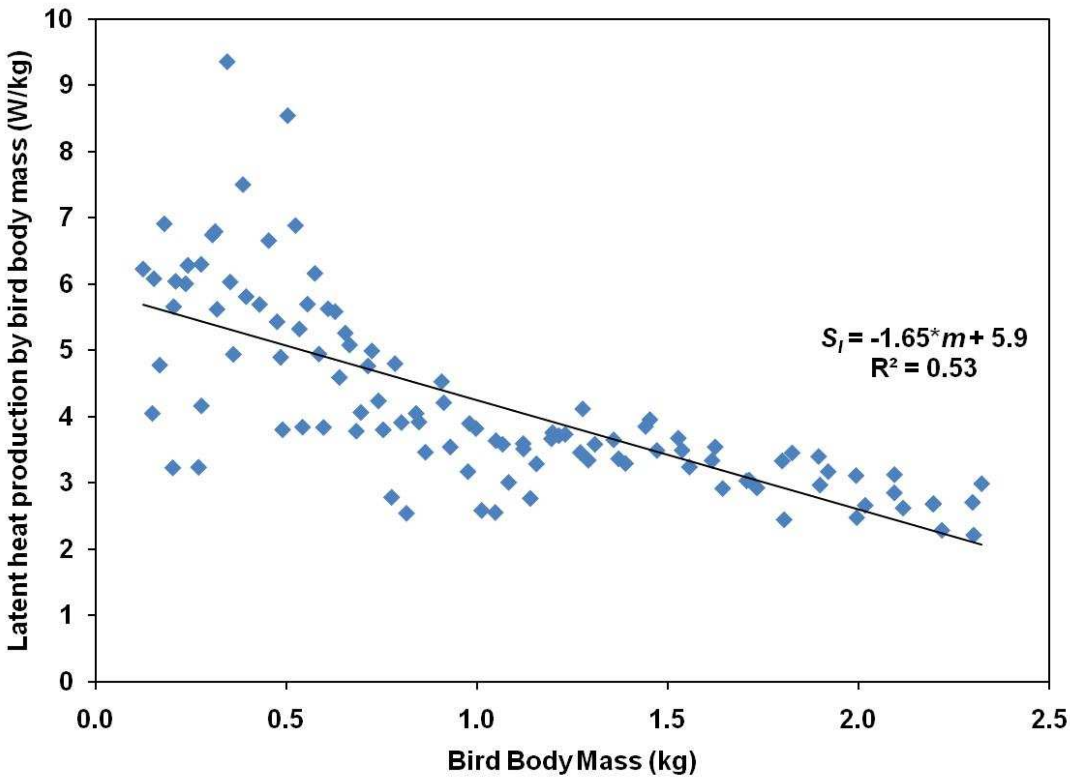

Figure 4.8: Latent heat production rate (S_l) per kg of broiler mass (m) averaged for the batches raised during the winter of 2008-2009. The latent heat production was corrected to eliminate air moisture ratio between the floor and ceiling and the variability in fan ventilation rate.

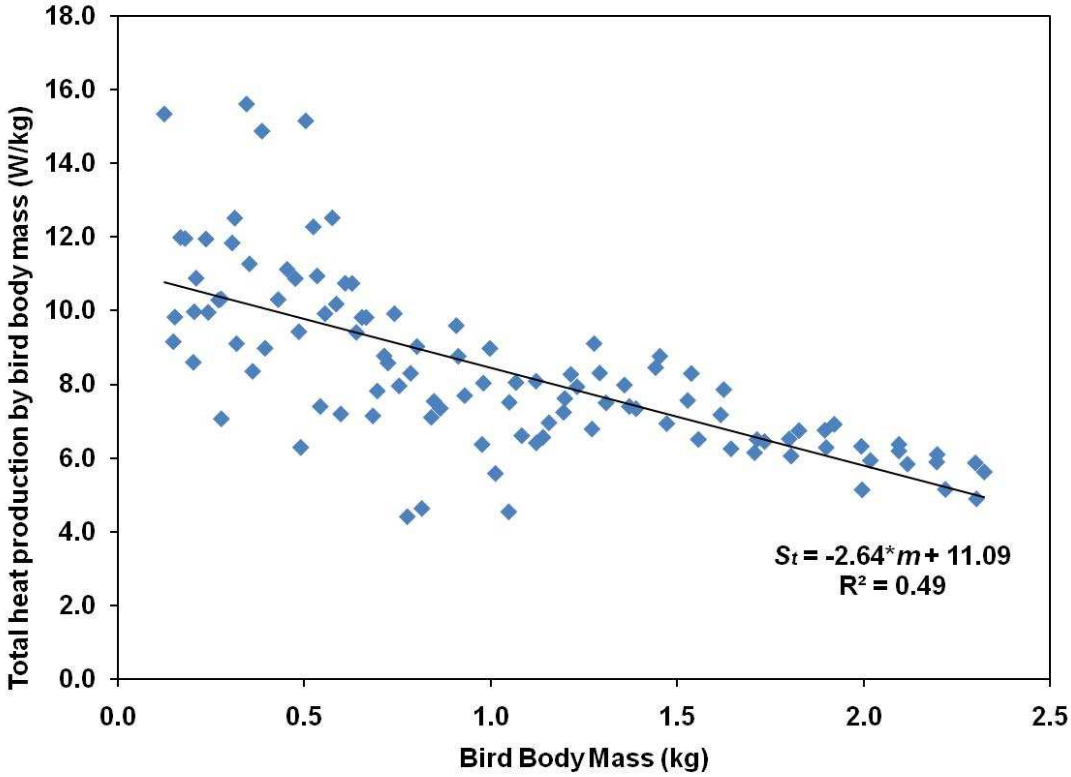

Figure 4.9: Corrected total heat production rate (S_t) per kg of bird body mass (m) averaged for the batches raised during the winter of 2008-2009. The calculated heat production was corrected to remove the heat conducted between floors and the variation in fan air flow rate.

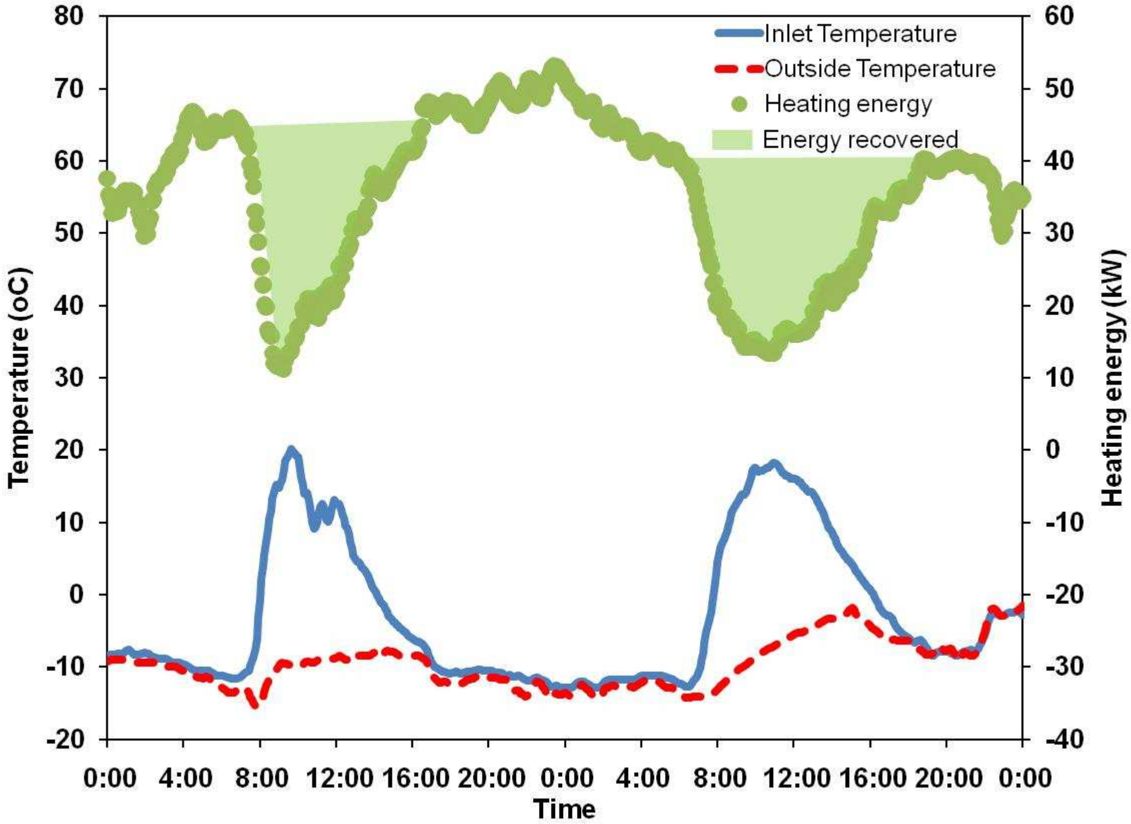

Figure 4.10: Heating load reduction with warmer inlet air temperatures resulting from energy recovered by the solar air pre-heaters, for two typical days of February 24th and 25th, 2009. The heating load on floor 2 of barn B was reduced by 432 and 540 MJ/day, respectively. The ventilation rate remained constant.

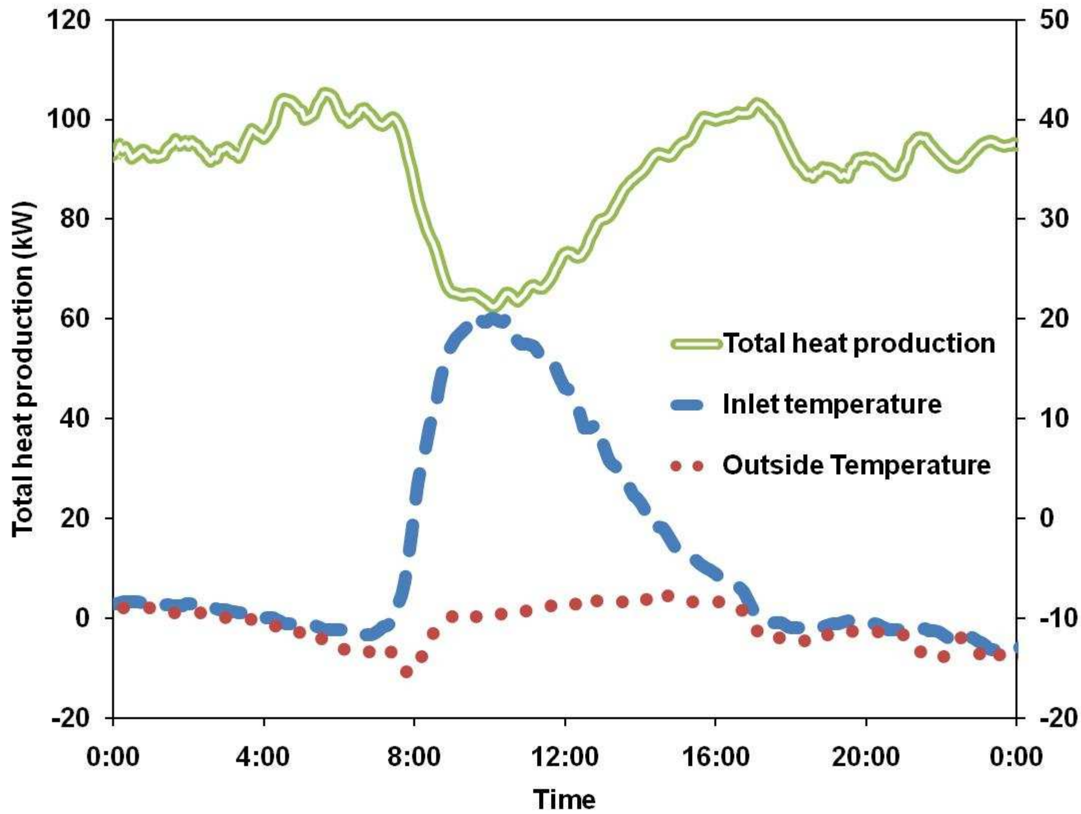

Figure 4.11: Calculated bird total heat production rate (S_{tc}) during a typical sunny day (February 25th, 2009) when the solar air pre-heaters produced an important increase in inlet air temperature. Accordingly, more buoyant fresh air at the inlet results in a short circuiting phenomenon towards the fan where a much lower air temperature is measured along with a drop in the calculated S_{tc}.

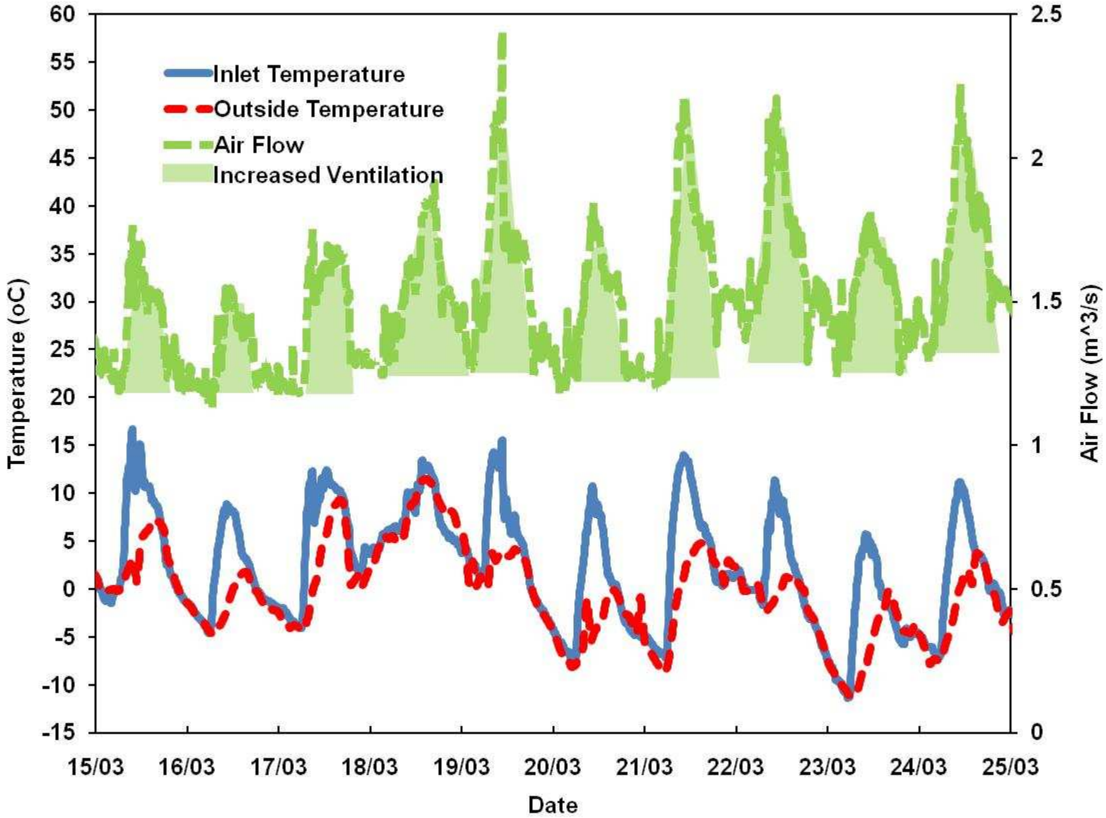

Figure 4.12: Increased ventilation rate resulting from a higher air temperature at the inlet. The solar air pre-heaters produced higher inlet air temperatures on March 15th to 25th 2009, except for March 17th and 18th, where the higher ventilation rate resulted from warmer exterior conditions. The solar air pre-heaters recovered enough solar energy to increase the ventilation rate mainly during March of each year. During the winter of 2008-2009, the solar air heaters increased the daytime ventilation rate during 20% of the time.

Connecting Statement to Chapter 5

To evaluate solar air pre-heaters efficiency and to conduct a heat balance, a good data acquisition system is essential. Chapter 5 describes the data acquisition system used in this project and its performance, as well as strategies to improve its monitoring accuracy for future similar research projects.

This chapter is drawn from an article prepared for publication in the Journal of Energy and Buildings. The manuscript was co-authored by Sebastien Cordeau, M.Sc candidate at McGill University and Dr. Suzelle Barrington, Supervisor and Professor at McGill University. The format has been changed to be consistent with this thesis.

Chapter 5: Instrumentation strategies for energy conservation in broiler barns with ventilation air solar pre-heaters

5.1 Introduction

Besides recent oil reserve uncertainties and increasing energy costs, the world's dependence on fossil-fuels has brought about growing concerns for global warming and climate change. World fossil-fuel resources are said to run out by 2050, considering the current consumption rate of 85 million barrels/day versus a total reserve of 1316 billion barrels (Thompson and Duggirala 2009; Abbott 2009; U.S. Energy Information Administration 2006). Accordingly, new approaches are needed in terms of energy conservation and efficient consumption, and the development of renewable energy sources (St-Denis and Parker 2009), such as from wind, geothermal sources, hydrogen, bio-fuels, solar and tides (Sovacool and Watts 2009; Schilling and Esmundo 2009). These renewable energy sources will meet our requirements when demonstrated to be efficient, reliable and cost effective. Consequently, oil based systems may still be needed as back-up to renewable energy sources.

To evaluate with confidence the heating energy performance of any building, including that from renewable sources, an accurate data acquisition system is essential to conduct energy balance analyses. However, in reality, gathering accurate data on energy balance is not easy because heat can be lost at specific points inside a building and, for commercial applications, environmental conditions can challenge the choice of monitoring instruments (Macleod 2008; Gates et al. 2001; Benhazi 2009). In livestock barns for example, ambient air dust, noxious gases and water vapour affect the accuracy of data acquisition sensors. Dust layers insulate and shield sensors leading to the inaccurate measurement of temperature and relative humidity. Noxious gases and high air relative humidity can oxidize expensive sensors and make them inoperative. The placement of sensors is limited by the presence of animals capable of damaging them and getting hurt or intoxicated. The placement of temperature sensors is crucial and heat displacement is often a better indicator of energy losses (Macleod 2008). Resulting from poor air mixing or low ventilation rates, air temperature stratification is a main challenge in monitoring building energy balance (Wheeler et al. 2000).

In this project, two commercial and identically built boiler barns, equipped with 220.8 m^2 of solar air pre-heaters at their ventilation inlets, were instruments to identify energy conservation strategies. The objective of this project was to evaluate the performance of the simple data acquisition system installed to measure inside and outside air conditions, ventilation rate and solar energy recovery. The solar air pre-heaters consisted of a wood frame box built over each fresh air inlet with an unprotected facing of perforated black corrugated metal sheeting through which fresh air was drawn by the barn ventilation system. Before entering the barn through the ventilation inlets, the cold fresh air flowed over the perforated metal sheeting, through the perforation and behind the sheeting (See Chapter 3).

5.2 Instrumentation of experimental buildings

5.2.1 Experimental buildings

The two experimental and identically built broiler barns A and B were located in St-Jean-Baptiste, 40 km east of Montreal, Canada, at 45.5° latitude. They each measured 9.2

m in width and 61 m in length where 57.9 m was used to raise broiler chickens. Barns A and B each offered three floors with an inside height of 2.7 m identified as A1, A2 and A3, and B1, B2 and B3, respectively. Barns A and B were part of a group of 12 parallel broiler barns built 58 m apart, where barn A was north of barn B. The fresh air inlets were installed on the long wall facing the southeast at an angle of 50° from the south, and were equipped with solar air pre-heaters measuring 1.47 m in height/floor and totalling 50.1 m in length, for 73.6 m^2 of solar air pre-heater/floor or 220.8 m^2/building. The solar air pre-heaters consisted of a wood frame box built over each fresh air inlet (Figure 5.1). Its unprotected facing of black corrugated metal sheeting had small perforations covering 1% of its surface. Before entering the barn through the inlets, the cold fresh air flowed over the perforated metal sheeting, through the perforation and behind the sheeting (See chapter 3). The solar air pre-heaters could be bypassed by opening the bottom portion of the wood frame box.

Both barns offered three floors with a capacity of 6 500 broiler chickens/floor. The chickens were raised in batches, from the age of 7 to 40-50 days and from 0.035 to 2.5 kg in body mass. For any given barn, all three floors were filled and emptied at once. During the cold season and once the broilers were freshly introduced into the barns, only two 400 mm fans/floor were operated at a minimum speed of 55% (0.43 m^3/s/fan). The speed of these exhaust fans was increased from 55 to 100% (0.94 m^3/s per fan) over a temperature increment of 1.4°C. An automated control system increased the fan air flow rate in parallel with a higher air temperature difference between that set-point and that measured by three central thermocouples distributed over the building length at a height of 0.3 m off the floor. Sensors T_1, T_2 and T_3 in Figure 5.2, were located next to these three thermocouples. The initial temperature set-point of 32°C was dropped by 0.27°C/day to 24°C. After one to three weeks, a third 400 mm fan was placed in operation and all three fans handled the fresh air ventilation rate until the end of the batch. During the experimental period covering the winter months, the ventilation rate generally remained at its minimum level of 0.86 (first 2 to 3 weeks with two 400 mm fans operated at 55% of their maximum speed) or 1.14 m^3/s (thereafter with three 400 mm fans operated at 55% of their maximum speed), while the gas heaters were operated regularly.

5.2.2 The data logging system

Data was recorded inside both experimental broiler barns using Hobo Energy Logger Pro data loggers (Onset Computer Corporation, Pocasset, MA, USA). One logger was installed in the centre of each floor to record air temperature and relative humidity, heating time and ventilation air flow rate (Figure 5.2). Carbon dioxide was recorded only on floor 2 of each barn, in the centre of the room and at a height of 1.5 m. Installed on a 3.0 m high tower located in a grassed area mid way between barns A and B, a weather station recorded wind velocity and direction, ambient air temperature, barometric pressure and relative humidity, and absorbed horizontal and vertical radiation. The weather station data was recorded using a HOBO Weather Logger data logger (Onset Computer Corporation, Pocasset, MA, USA).

5.2.3 Temperature measurement

Temperature was monitored inside the buildings using six sensors/floor. Five sensors measured only temperature (8-bit Temperature Smart Sensors, HOBO S-TMA from Onset Computer Corporation, Pocasset, MA, USA) with an accuracy of ± 0.7°C and a resolution of 0.4°C. This level of accuracy was verified prior to the installation by recording the air temperature of a room with all sensors. The sixth sensor (T_2) measured both temperature and relative humidity (12-bit Combined Temperature and Relative Humidity Smart Sensor, HOBO S-THB from Onset Computer Corporation, Pocasset, MA, USA) with an accuracy of 0.2°C and a resolution of 0.02°C. On each floor, temperature sensors T_1, T_2 and T_3 were installed centrally at 0.3 m off the floor (Figure 5.2) and the mean obtained provided a value for the inside air temperature. Sensor T_4 measured the outgoing air temperature at a fan operated continuously. Sensors T_5 and T_6 measured the temperature of the incoming fresh air after the solar air pre-heater, and the mean obtained provided a value for the inlet air temperature. The outside air temperature was recorded using an 8-bit Combined Temperature and Relative Humidity Smart Sensor (HOBO S-THA from Onset Computer Corporation, Pocasset, MA, USA) installed as part of the weather station. To better understand the impact of ventilation on room air temperature, infrared pictures were taken inside the barns.

To verify the accuracy of the temperature sensors, exterior temperature readings were compared to those measured by the St-Hubert Environment Canada weather station located 15 km east of the experimental site.

5.2.4 Relative humidity measurement

Air relative humidity was recorded at only one location on each floor using a 12-bit Combined Temperature and Relative Humidity Smart Sensor (HOBO S-THB from Onset Computer Corporation, Pocasset, MA, USA) with a resolution of 0.1% and an accuracy of 2.5% for readings between 10 and 90%. Air relative humidity measurement was combined with temperature (T_2) and was consequently located in the centre of the room at 0.3 m off the floor (Figure 5.2). The exterior air relative humidity was also recorded by the weather station using an 12-bit Combined Temperature and Relative Humidity Smart Sensor (HOBO S-THB from Onset Computer Corporation, Pocasset, MA, USA).

5.2.5 Ventilation air flow measurement

The ventilation air flow rate of the fan at T_4 was measured by converting the fan rpm into a 0-5V signal recorded by the data logger (Heber et al. 2001). To monitor the fan rpm, two magnets and one Hall Effect sensor were used. The magnets were mobile and glued to fan blades while the Hall Effect sensor was stationary and attached to the fan frame. Moving past the Hall Effect sensor, the magnets created a magnetic field impulse sent to a 0-5V signal converter. This converter used a PIC16F690 micro-controller (Microchip Technology inc, Chandler, Arizona, USA). A Balometer (ALNOR EBT721 Balometer, Huntingdon Beech, CA, USA) was used to measure the ventilation rate of all eighteen 400 mm fans against their rpm values, to relate the 0-5V signal to the fan air flow rate.

5.2.6 Radiation measurement

Solar radiation can be measured using different instruments such as a ultra-violet (UV) radiometer, a pyrheliometer, or a pyranometer. The UV radiometer measures the spectral irradiance and monitors UV-A and UV-B rays. The pyrheliometer is especially made to measure direct solar radiation facing the instrument, while the pyranometer measures the total irradiance absorbed by a plane surface. In this project, solar radiation was measured using two pyranometer sensors (Model S-LIB Hobo Silicon Pyranometer Smart Sensor, Onset Computer Corporation, Pocasset, MA USA) with an accuracy of ± 10.0 W/m^2 or ± 5%, whichever is greater in sunlight. In addition, temperature was said to induce an error of 0.38 $W/m^2/°C$ above 25°C. The HOBO silicon pyranometer radiation sensors use silicon photodiodes to measure solar power with a spectral range of 300 to 1100 nm, which does not exhibit an equal spectral response for solar wave lengths of 280 to 2800 nm. Nevertheless, this error is negligible when the sensors are calibrated to measure natural sunlight (Onset Computer Corporation, Pocasset, MA USA).

The radiation values measured by the horizontal pyranometer sensor were validated against those obtained from the Varennes Environment Canada weather station using a pyranometer LI-200S from Li-Cor Inc (Lincoln, Nebraska, USA) and located 30 km northwest of the experimental site.

The weather station pyranometer sensors were installed at a height of 3 m off the ground. The first was placed horizontally while the second was place vertically and parallel to the southeast barn walls using a handheld compass, to respectively measure the horizontally absorbed solar radiation and the solar radiation absorbed by the solar air pre-heaters. The vertical pyranometer sensor measurements were compared against theoretical values (ASHRAE 2009):

$$R_a = E_{DN} + E_r + E_d \tag{1a}$$

$$= I \times [Cos\ \theta + (C + \sin(\beta) * \rho_g) \times 0.5 + (C \times y)] \tag{1b}$$

$$= [A / e^{\{B/\mathrm{Sin}\,(\beta)\}}] \times [Cos\ \theta + (C + \sin(\beta) * \rho_g) \times 0.5 + (C \times y)] \tag{1c}$$

where R_a is the absorbed solar radiation in W/m^2, E_{DN} is the absorbed direct solar irradiance in W/m^2, E_r is the ground reflected solar irradiance in W/m^2, E_d is the diffuse solar irradiance in W/m^2, I is the incident radiation W/m^2, θ is the angle of incidence of the solar radiation on the absorbing surface in degree, A, B and C are dimensionless coefficients changing with the day of the year n, where January 1st is n = 1 and December 31st is n = 365, and used to calculate the absorbed radiation. β is the sun's altitude in degree of arc, ρ_g is the coefficient of ground reflection generally equal to 0.2, and y is a dimensionless coefficient used to evaluate the diffused absorbed radiation.

5.2.7 Heating measurement

The operating time of the heating system was measured using two techniques: manually noting the daily operating time compiled by the barn's automated ventilation control system, and; using a 5 volt AC adapter plugged into the 120V AC power outlet controlling the heaters. This AC adapter sent a signal to the data acquisition system when the heaters, two on each floor, were operated and this signal was recorded as% operation time every 5 min.

On each floor, the two natural gas heaters generated 60 kW of heat computed from their natural gas consumption containing 98% CH_4 (Metropolitan Gas, Montreal, Canada). Also, the heaters were assumed to generate moisture, at a rate of 2.246 kg/kg of CH_4 combusted, based on stoichiometry (ASHRAE 2009). The total heat energy released by the natural gas heaters on each floor was computed from the% of operating time.

5.3 Result and Discussion

5.3.1 Temperature measurement

To evaluate the accuracy in measuring air temperature, the readings obtained with the weather station temperature sensor were compared to those measured by the St-Hubert Environmental Canada weather station (Table 2). The outside temperature measurements were found to be reliable, with a value within 0.2°C on average with a standard deviation of 0.24 of those measured by the St-Hubert Environmental Canada weather station.

To verify if six HOBO temperature sensors were sufficient inside the barns to conduct an energy mass balance, the broiler sensible heat production rate was calculated based on ventilation air flow rate. Accordingly, the following sensible heat balance equation was used:

$$S_e = (Q \times \rho_a \times (T_t - T_i) \times C_p) + \{\Sigma A_i / R_i \times (T - T_e)\} - H_s \qquad (2)$$

where S_e is the calculated sensible heat production rate in kW for N birds weighing m kg in body mass, Q is the ventilation rate in m^3/s, ρ_a is the density of the inside air at the exhaust fan in kg/m^3, T_i is the average temperature of the inlet air in°C measured using sensors T_5 and T_6, T_t is the temperature of the inside air at the exhaust fan in°C measured using sensor T_4, C_p is the specific heat of air of 1.006 kJ/kg dry air/°C, A_i is the shelter surface in m^2 associated with an insulation value R_i in m^2°C/kW, T is the inside air temperature in°C averaged from the reading of sensors T_1, T_2 and T_3, T_e is the outside air temperature in°C measured by the weather station sensor and H_s is the heater sensible heat production rate in kW. In Equation (2), heat lost by air infiltration was presumed negligible.

Based on Equation (2), Figure 5.3 illustrates the calculated sensible heat S_e produced by the 10th batch of 6 500 birds/floor for building A, on floors 1, 2 and 3 (A1-10, A2-10, A3-10) respectively, from January 30th to March 7th, 2009. For 6 500 birds weighing 0.035 kg, Equation (2) gives a sensible heat production rate of 2.5 kW (Hellickson and Walker 1983) for floor 1, which is similar to that expected (Hellickson and Walker 1983), but 20 kW higher for floors 2 and 3. To calculate the heat lost by the ventilation system and the building shell, Equation (2) relies on the main assumption that the room air is perfectly mixed. To view the heat distribution on the floors, infra-red pictures were taken on February 18th 2009, inside barn B and in the absence of birds (Figure 5.4 and 5.5). Air temperature stratification was clearly observed, with the heaters creating higher temperatures on the left side and ceiling air offering temperatures 10°C higher than that at the floor. The barn ceilings consisted of 16 mm plywood wetted by washings between batches, and covered with an uneven 50 mm layer of damp litter (15% moisture content). Accordingly, offering an insulation of 270 m^2°C/kW (ASHRAE 2009), the ceiling can conduct 20 kW with a temperature difference of 10°C. Since such air temperature stratification creates 20 kW of heat loss for floor 1, but 20 kW of heat loss and gain for floors 2 and 3, then all floors produced 20 kW more sensible heat production rate expected. The measured heater operation time was found to correspond to that recorded by the automated ventilation control system, leaving the ventilation rate as the main source of error in computing the bird sensible heat production rate using Equation (2).

5.3.2 Relative humidity measurement

To evaluate the accuracy in measuring the inside air relative humidity using sensor T_2, a latent heat balance was conducted based on the ventilation air flow rate. Accordingly, the following sensible heat balance equation was used:

$$S_l = (Q \times \rho_a \times (W_i - W_e) \times h_{fg}) - H_l \qquad (3)$$

where S_l is the calculated sensible heat production rate in kW for N birds weighing m kg in body mass, Q is the ventilation rate in m^3/s, ρ_a is the density of the inside air at the exhaust fan in kg/m^3, W_i is the inside air humidity ratio in kg water/kg dry air calculated from the relative humidity measured by the combined sensor T_2 in the room centre at 0.3 m off the floor and the temperature at the exhaust fan, W_e is the outside air humidity ratio calculated from the relative humidity and temperature measured by the combined weather station sensor in kg water/kg dry air, h_{fg} is the heat of vaporization of water of 2450 kJ/kg water and H_l is the heater latent heat production rate in kW. In Equation (3), moisture lost by air infiltration was presumed negligible.

Figure 5.6 illustrates the calculated latent heat S_l produced by the 10^{th} batch of 6 500 birds/floor for building A, and on floors 1, 2 and 3 (A1-10, A2-10, A3-10) respectively from January 30th to March 7th, 2009. For 6 500 birds weighing 0.035 kg, an initial latent heat production of 0.5 kW was expected (Hellickson and Walker 1983), while Equation (3) gives a value in the range of 20 kW for all three floors. This difference once more results from the stratification of air inside the rooms and the fact that S_l was calculated from the air moisture ratio at 0.3 m off the floor when that of the exhausted air at the fan is likely drier. Once more, inside air mixing through the ventilation system would facilitate the monitoring of relative humidity.

5.3.3 Ventilation air flow measurement

Measuring the ventilation air flow rate of livestock barns is challenging, because the control algorithm uses at least four levels which may be changed by the operator to improve ambient inside air conditions solely controlled by temperature. In livestock barns, the control algorithm starts with a continuous minimum ventilation rate, which is increased based on the difference between the set-point of each level and the ambient air temperature. Therefore, at the start of the project, the air ventilation rate was computed from the ventilation algorithm and by measuring every 20 minutes, the inside air temperature beside the thermostats feeding data to the automated ventilation control system. By comparing the computed ventilation rates to that recorded by the automated ventilation control system, this method was found inadequate. Even 5 min recording intervals did not correct the problem, because ventilation rates varied over shorter periods.

An electromagnetic device was introduced to directly measure ventilation air flow rate based on its rpm. It proved more accurate, providing data corresponding to that registered by the automated ventilation control system. To relate fan rpm to air flow rate, a balometer (ALNOR EBT721 Balometer, Huntingdon Beech, CA, USA) was used with an accuracy of ± 3%. Figure 5.7 gives the average ventilation rate measured as a function of fan speed set by the automated ventilation control system. The rpm measurements were presumed to be able to measure the effect of dust and wind on fan air flow rate. Depending on direction, wind created against the fans either a positive or negative pressure with a magnitude depending on fan position on the floor and between floors. Dust reduced the fan air flow rate by freezing in layers on the blades and housing as a result of moisture condensation.

Nevertheless, during the duration of all bird batches, a relatively constant error ranging from 20 to 40 kW was observed when computing broiler sensible heat production rate, with the higher value being associated with batches raised under lower exterior temperatures and higher wind speeds (See chapter 3). This error is associated with the fact that only one fan/floor among the three was monitored for air flow rate and air temperature and relative humidity. Properly monitoring the ventilation air flow rate of any building therefore requires the rpm and air condition parameters at all exhaust fans.

Measuring inside air CO_2 levels is another technique used to monitor ventilation rate. In this experiment, the selected CO_2 sensor was limited to 2500 ppm while inside air concentration often exceeded 4000 ppm. Such high CO_2 levels resulted from the natural gas heaters releasing their exhaust inside the rooms to save energy. The use of CO_2 sensors capable of measuring up to 5000 ppm is preferred for any barn with natural gas or propane heaters.

5.3.4 Solar Radiation measurement

The two solar radiation sensors installed on the weather station were found to give accurate results. Values measured at the experimental site with the horizontal radiation sensor followed the same trend as those measured by Environment Canada except for the peak value which was generally 5 to 7% higher at the experimental site (Figure 5.8). This resulted from the fact that the Varennes Environment Canada weather station was 30 km away from research site and sky conditions can be different even on clear days. Moreover, radiation sensors had an accuracy of 5% or 10W/m^2, whichever is larger. In Figure 5.8, less radiation is observed at the experimental site as compared to Varennes before 8h30, because the weather station was located between the two 12 m high experimental barns and when the sun was low, the southern building shadowed the sensors. Since the solar air pre-heaters on the barn walls were not shadowed by each other, installing the experimental pyranometers next to the solar air pre-heater would be preferred. Nevertheless, accurate wind speed measurement requires being away from the buildings.

The values obtained with the vertical radiation sensor, facing the southeast and parallel to the solar air pre-heaters, were compared to those calculated using Equation (1). In general all values corresponded except for late in the afternoon, when only diffused and reflected radiation was absorbed. Governing the value of the reflected radiation, the ground reflectance coefficient changed with season and ground cover. Figure 5.9 shows an acceptable error of 4%, on April 6th, 2008, for a ground reflectance coefficient ρ_g of 0.2 associated with a green grass cover. On February 14th, 2008, Figure 5.10 shows that a ground reflectance coefficient of 0.6 rather than 0.2 better represents a snow cover, otherwise radiation values were off by 20% in late afternoon.

Accordingly, when computing absorbed radiation values using Equation (1), the following ground reflectance coefficients are recommended: for summer conditions and a grass ground cover, 0.2; for a light snow cover, 0.4, and; for a full snow cover, 0.6.

5.3.5 Heating measurement

The AC adapter monitoring heating time gave results comparable to the data gathered by the automated ventilation control system. Furthermore, the AC adapter provided data pertaining to the exact time of heater operation which could then be used to complete the energy balance and evaluate the impact of the solar air pre-heater. Figure 5.11 shows a reduction of 432 and 540 MJ in heating load on February 24th and 25th, 2009, as a result of heat picked up by the solar air pre-heaters.

5.3.6 Operation of instrument

Because the two experimental barns were located in a rural setting, no high speed internet connection was available to electronically transmit the data. Data transmission by cellular network was tested during the first year with interference problems. For the data properly transmitted, there was often a one week interval between data collection and appearance on the web site of the service provider. Therefore, the best method consisted in regularly downloading the recorded data on a portable computer, considering also that the experimental site was visited regularly to maintain the instruments.

Furthermore, the instrument operation was changed during the experiment. Initially, a 20 minute recording interval was selected to provide more data logging flexibility. But, a 20 minute interval was found to be too long, as the data gave a snapshot rather than an average view of air quality. For example, if the heating system was operating while the logger was registering, all sensors showed a temperature much higher than the average over the past 20 min. To improve data collection while still respecting the logger storage memory of 45 days, a 5 minute sampling time interval was chosen.

5.3.7 Strategies to improve heating energy efficiency

In this project and for all bird batches monitored, air temperature stratification was observed to explain the conductive heat transfer between floors of 20 to 40 kW (See chapter 4). This conductive heat loss was found to increase with lower outside temperatures and higher wind velocities, generally requiring more heating. Because floor 1 lost heat while floors 2 and 3 both gained and lost heat, the net effect is reflected by the higher heating requirements for floor 1. Accordingly and for the winter season, the natural gas heaters on floor 1 of both experimental barns were observed to run during 780 h as compared to an average of 620 h for floors 2 and 3. Some heat loss on floor 1 likely resulted in limited part, from the poorly insulated foundation (Figure 5.5). The use of a ventilation system maintaining the air inside a building mixed at all times can therefore improve heating efficiency by 25%, while simplifying heat balance monitoring using temperature sensors.

The energy recovery efficiency of the solar ventilation air pre-heaters was also affected by poor inside air mixing. Figure 5.12 illustrates the bird total heat production

(S_s + S_l) as calculated from Equations (2) and (3). The bird heat production dropped drastically every time the solar air pre-heaters quickly increased the temperature of the incoming fresh air by more than 10°C, and the effect was worse when, as a result, the ventilation rate increased. This warmer fresh air was likely more buoyant and evacuated by the fans before refreshing the inside air, a process called short-circuiting. Such a process produced an air temperature at the exhaust fan which was lower than the average inside the room, thus decreasing the apparent bird total heat production rate calculated from (S_s + S_l). Accordingly, some of the recovered solar energy was short-circuited and exhausted by the fans. Considering that such a phenomenon was observed to occur 20% of the time, from November to March, 15% of the energy recovered by the solar air pre-heaters can be presumed wasted.

5.4 Conclusion

The objective of this project was to evaluate the performance of a simple data acquisition system installed to conduct an energy balance analysis in two commercial broiler barns. The acquired data was used to evaluate the energy recovery efficiency of solar ventilation air pre-heaters and to help identify strategies to reduce winter heating loads.

The results obtained from this project propose the following improvements in instrumentation strategy to better monitor energy balance, and for the ventilation system to reduce heating load and recover more solar energy:

i) Ambient air temperature is likely the hardest parameter to monitor, unless inside temperature stratification is corrected by a mixing system. When conducting energy balance studies to improve heating efficiency, air temperature stratification is a key component leading possibly to high heat losses.

ii) Inside air relative humidity is also an ambient condition which varies with temperature and should be measured in parallel.

iii) Ventilation rate can be adequately measured by monitoring fan rpm using electromagnetic devices; nevertheless, all fans need to be monitored as wind and dirt can change their individual performance over time.

iv) Pyranometers can adequately measure absorbed direct, diffused and reflected radiation, but these need regular calibration based on manufacturer's recommendations; furthermore, when calculating the total absorbed solar energy, the ground reflectance coefficient ρ_g needs to be adjusted with season and ground cover.

5.5 References

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Table 5.1:Nomenclature

A, *B* and *C* are coefficients changing with *n* and used to calculate the absorbed radiation, dimensionless.

A_i is a shelter surface in m^2 associated with an insulation value R_i in m^2/kW-°C.

*C*p is the heat capacity of dry air or 1.006 kJ/kg dry air /°C.

CV is the coefficient of variation.

E_d is the diffuse solar irradiance in W/m^2.

E_r is the ground reflected solar irradiance in W/m^2.

E_{DN} is the absorbed direct solar irradiance in W/m^2.

h_{fg} is the heat of vaporization of water of 2450 kJ/kg of dry air.

H_s is the heater sensible heat production rate in kW.

H_l is the heater latent heat production rate in kW.

I is the incident radiation W/m^2.

m is the body mass of each birds.

n is the day of the year, where January 1st is $n = 1$ and December 31st is $n = 365$.

N is the number of birds.

Q is the ventilation rate offered by the ventilation system in m^3/s.

R_a is the absorbed solar radiation in W/m^2.

R_i is the insulation value of surface A_i in m^2/kW-°C

S_l is the calculated latent heat production rate in kW for *N* birds weighing *m* kg in body mass.

S_e is the calculated sensible heat production rate in kW for *N* birds weighing *m* kg in body mass.

T is the temperature of the inside air averaged from the reading of sensors T_1, T_2 and T_3, in °C.

T_i is the average temperature of the air at the inlets inside the building in °C.

T_e is the outside air temperature in °C.

T_t is the air temperature at the exhaust fan in °C.

W_i is the inside air humidity ratio in kg water/kg dry air.

W_e is the outside air humidity ratio in kg water/kg dry air.

y is a coefficient used to describe the diffused absorbed radiation, dimensionless.

β is the sun's altitude in degree of arc.

θ is the angle of incidence of the solar radiation on the absorbing surface in degree.

ρ_g is the coefficient of ground reflection generally equal to 0.2.

ρ_a is the density of dry air for the temperature measured at the exhaust fan in kg/m^3.

Table 5.2: Measured temperature compared to that observed by a nearby Environment Canada weather station.

Date	Average temperature (^{o}C)		
	St-Jean-Baptiste	St-Hubert	Difference
June 08	19.50	19.42	-0.08
July 08	20.77	21.08	0.32
August 08	18.90	19.18	0.27
September 08	16.00	16.20	0.19
October 08	7.92	8.07	0.14
November 08	2.61	2.49	-0.12
December 08	-6.23	-6.18	0.06
January 09	-13.59	-12.91	0.68
February 09	-7.40	-7.19	0.20
			Mean = 0.18, σ = 0.24

Figure 5.1: Solar air pre-heaters installed over the fresh air inlets. The bottom door was used to by-pass the solar air pre-heaters during the warm seasons otherwise this door is closed to force the ventilation air through the perforated black metal siding on the face of the solar air pre-heaters.

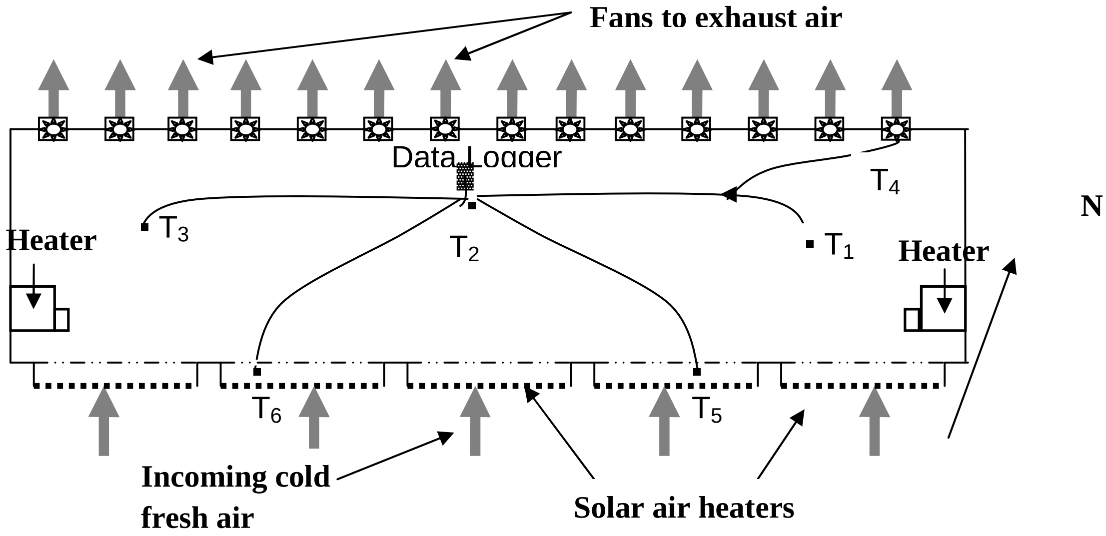

Figure 5.2: Instrumentation of experimental buildings where: T_1, T_2, T_3 are temperature sensors installed inside the building at 0.3 m off the floor, to measure the inside air temperature; T_5 and T_6 measure the temperature of the incoming fresh air at the inlet after the solar air pre-heater, and; T_4 measures the temperature of the outgoing air at a fan operated continuously.

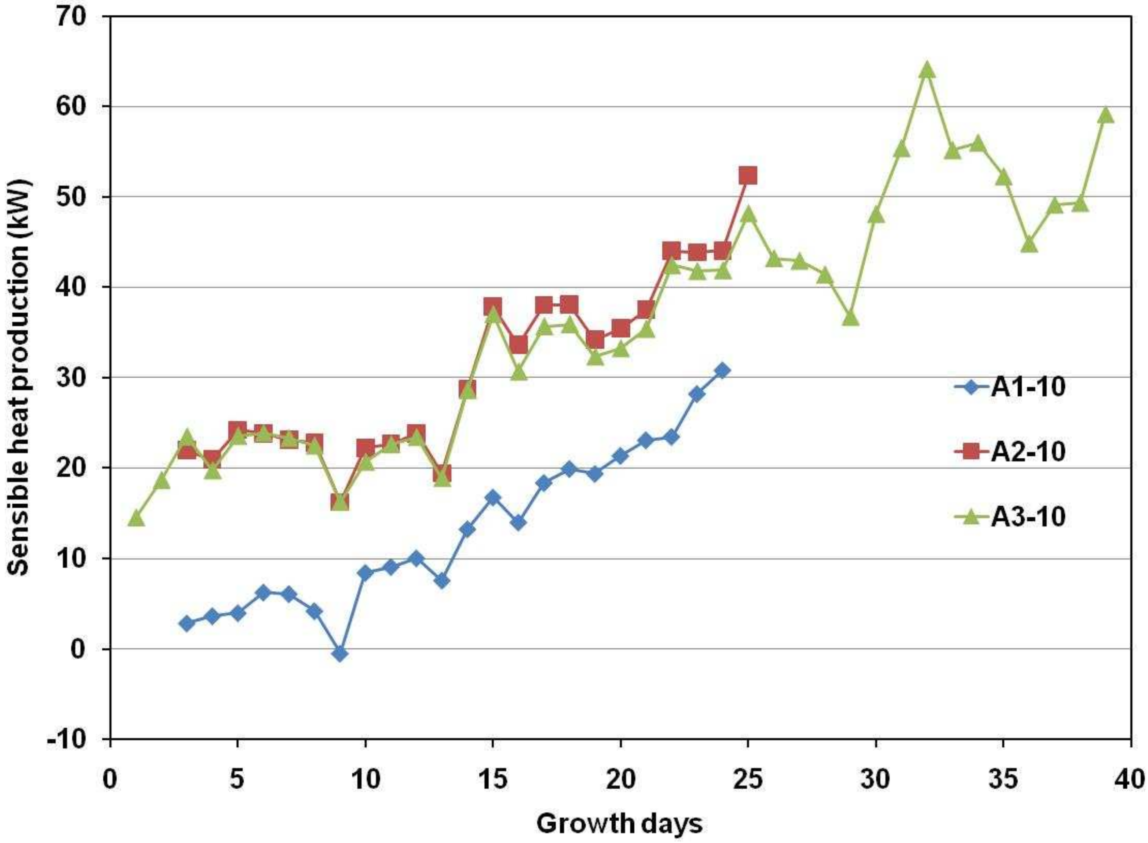

Figure 5.3: Calculated sensible heat production rate of 6 500 birds, for the 10th batch A1-10, A2-10 and A3-10 (floors 1, 2 and 3 respectively of barn A), from January 30th to March 7th 2009. As compared to that of A1-10, the calculated sensible heat production is higher for A2-10 and A3-10 because of air temperature stratification inside the rooms leading to heat flow through the ceilings by conduction.

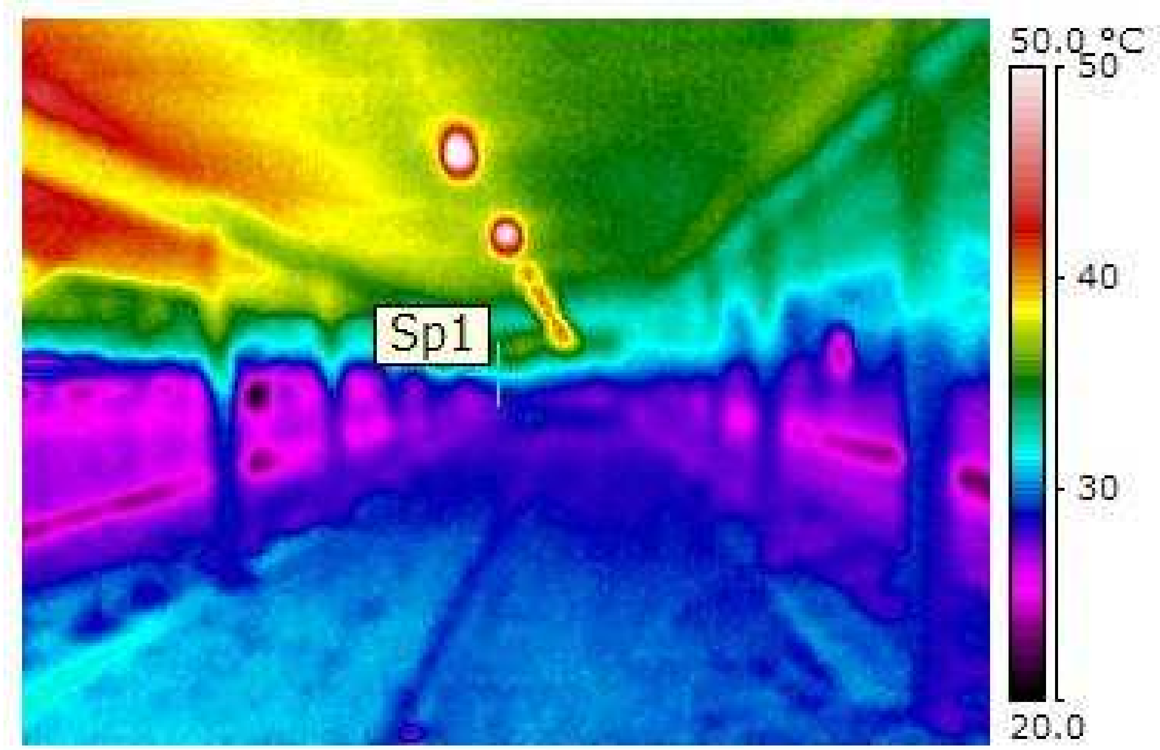

Figure 5.4: Infra-red view of the floor 1 inside barn B on February 18th, 2009, in the absence of birds but with the solar air pre-heaters (left) and the ventilation system (right) in operation. The high temperature at the ceiling on the left side is created by the heater (left) in operation. A 10°C difference in air temperature is observed between the ceiling and floor, explaining the conductive heat exchange between floors.

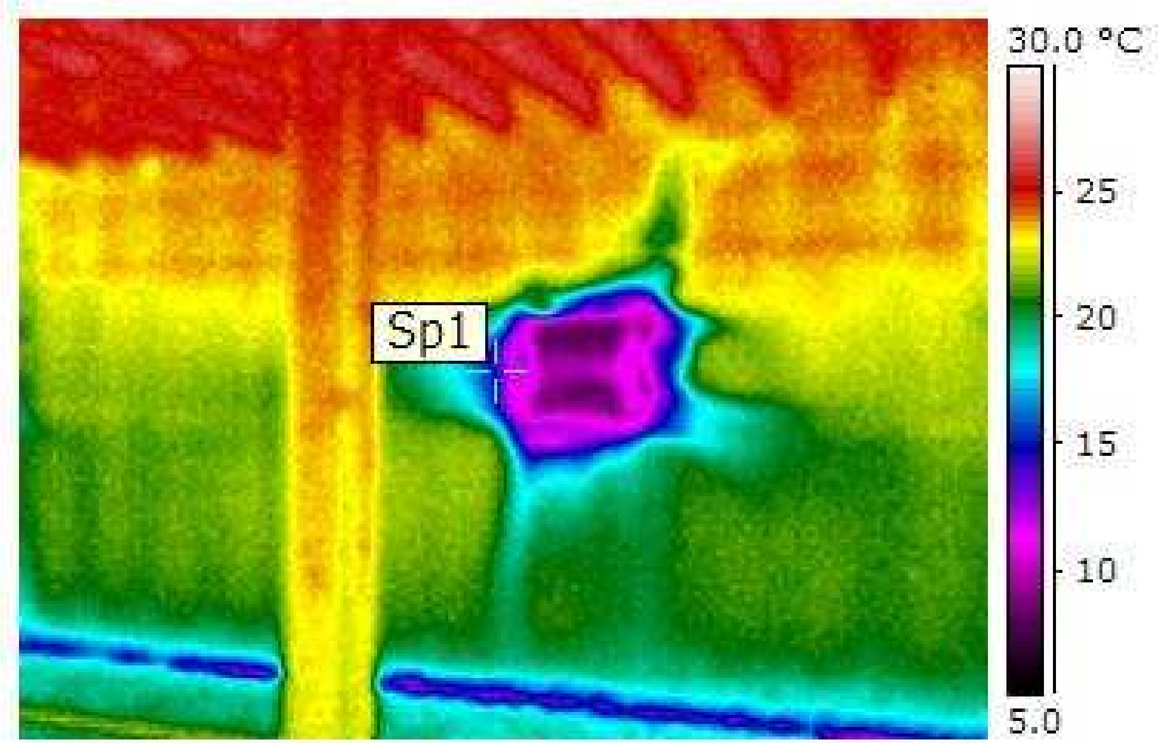

Figure 5.5: Infra-red view of the north wall of barn B on floor 1, for February 18th, 2009, in the absence of birds but with the solar air pre-heaters and the ventilation system in operation. Air temperature stratification is seen once more with a ceiling temperature of 28°C. The dark blue line close to the floor is the non-insulated foundation at 15°C, compared to the wall at 20°C. The fan temperature is illustrated by the circular 10°C surface at mid height on the wall.

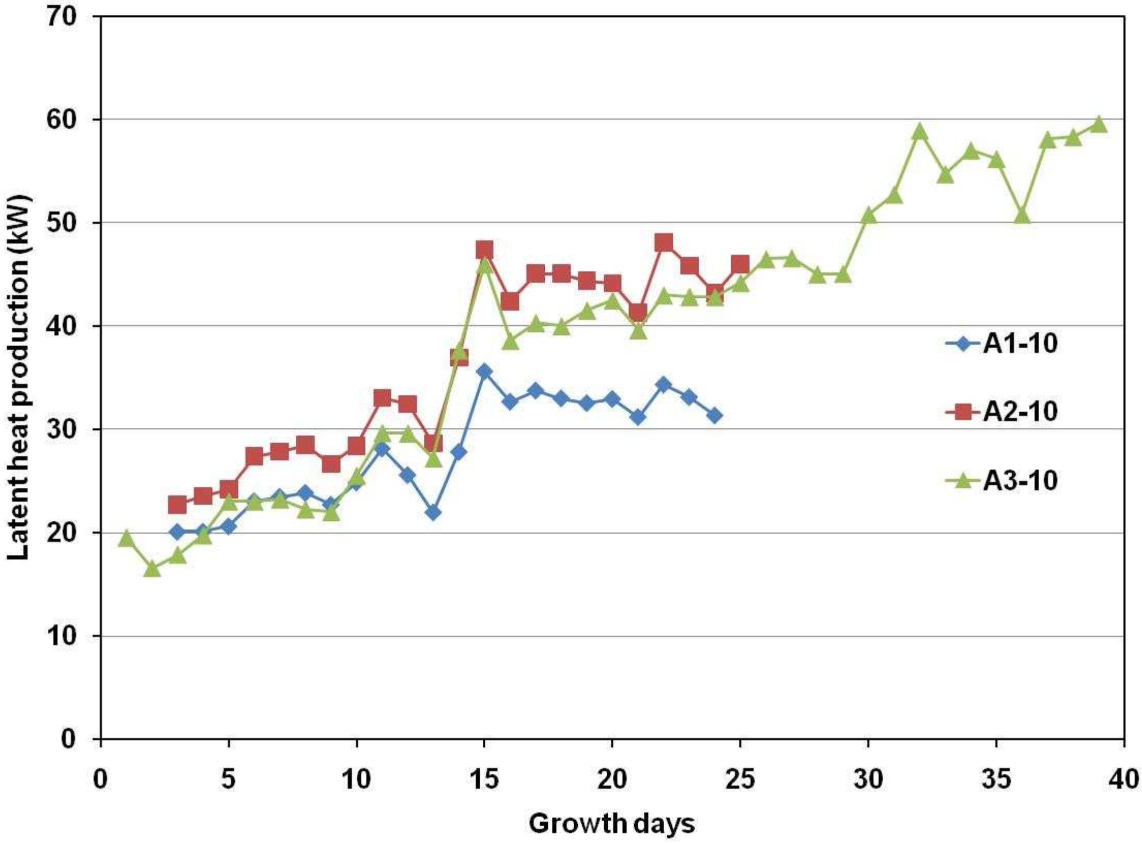

Figure 5.6: Calculated latent heat production rate of 6 500 birds, for batches A1-10, A2-10 and A3-10 (floors 1, 2 and 3, respectively, for barn A) from January 30th to March 7th 2009. The latent heat production rate is similar for all floors, indicating limited convective air transfer. The initial latent heat production rate exceeding that expected and common to all three floors indicates that the exhaust air had a lower moisture ratio compared to that at 0.3 m off the floor and used in the calculations, as a result of air stratification.

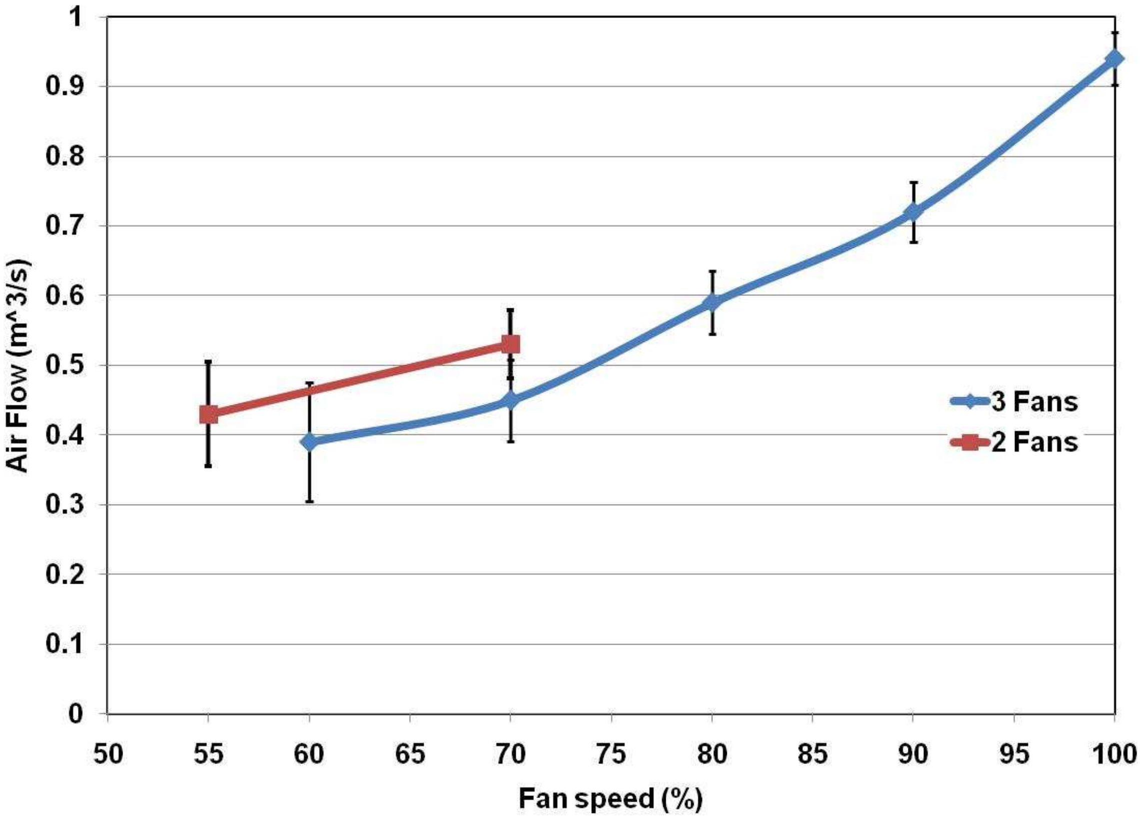

Figure 5.7: Average ventilation rate measured for the nine 400 mm inside diameter fans of the experimental building A as a function of fan speed.

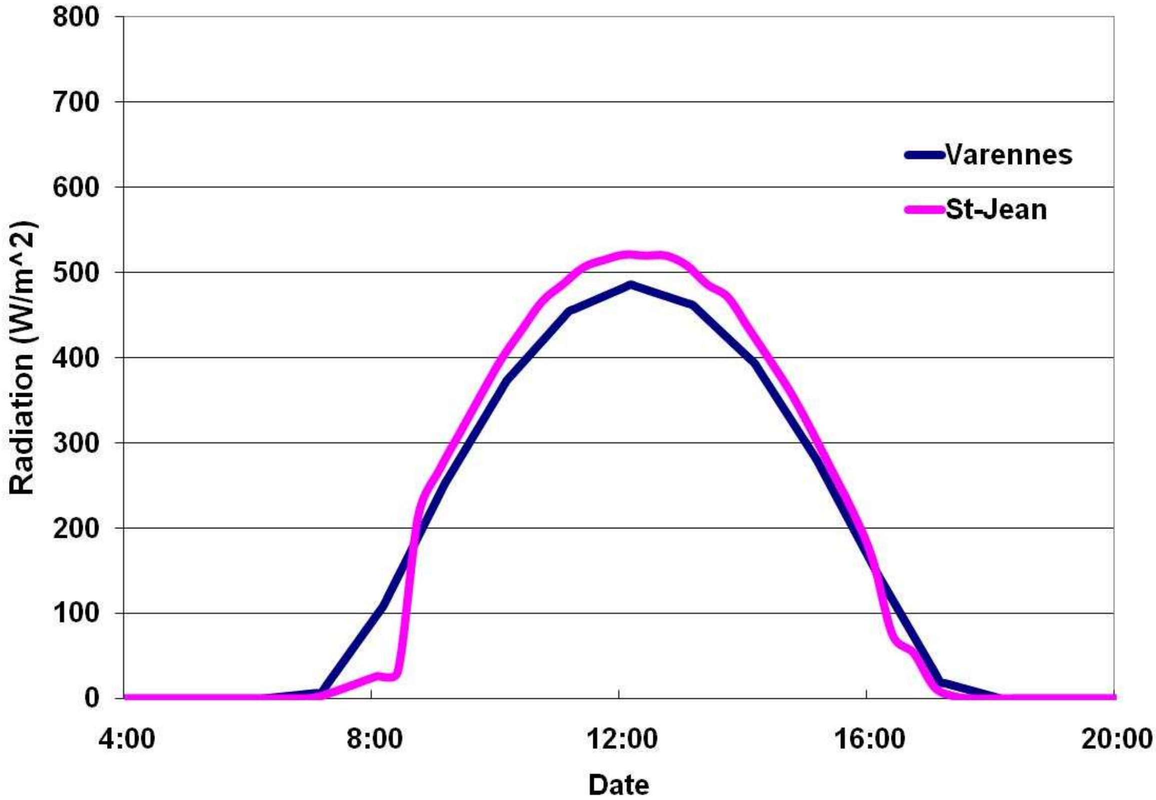

Figure 5.8: Comparison between the horizontal solar radiation values measured at the Varennes weather station of Environment Canada (Latitude 45.7°) and those measured by the horizontal Hobo silicon pyranometer radiation sensor used on the experimental site at St-Jean-Baptiste (Latitude 45.5°) on November 2nd , 2007.

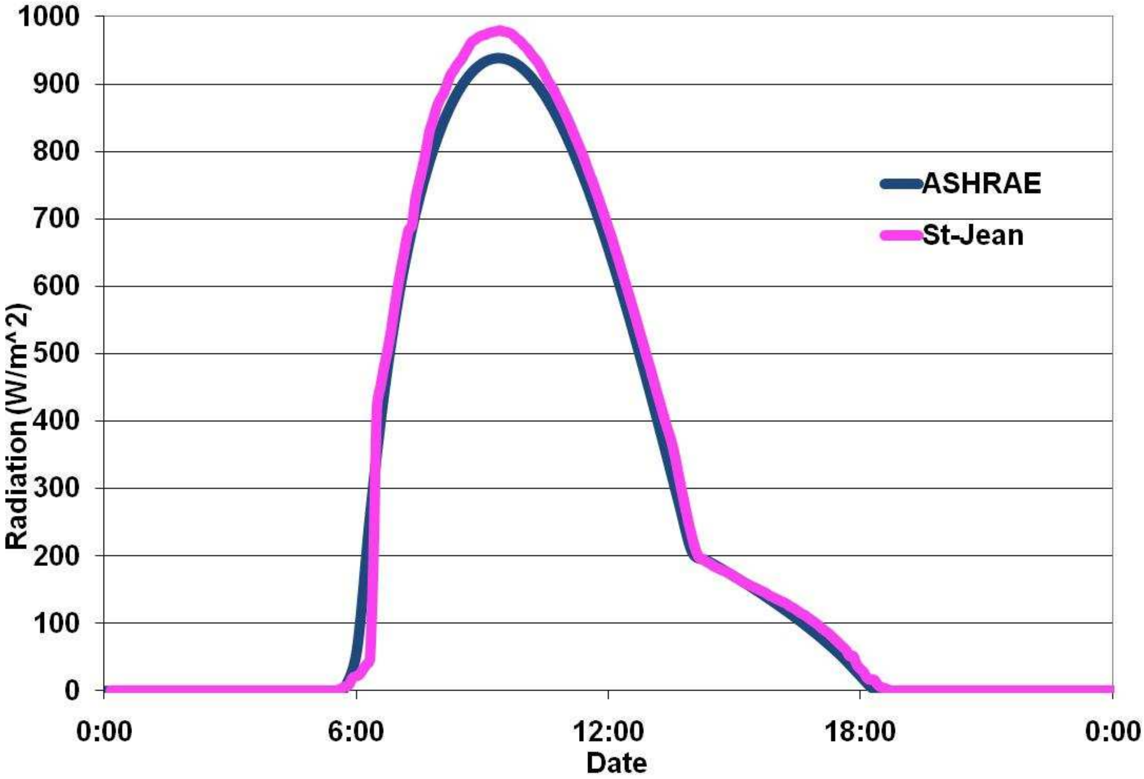

Figure 5.9: Comparison between the vertical absorbed solar radiation values measured by the vertical Hobo silicon pyranometer radiation sensor used on the experimental site (Latitude 45.5°), on April 6th, 2008 and that calculated using Equation (1); a ground reflection factor ρ_g of 0.2 produces values similar to those measured by the vertical sensor after 3:00 pm when the incident solar radiation is mainly that reflected and diffused.

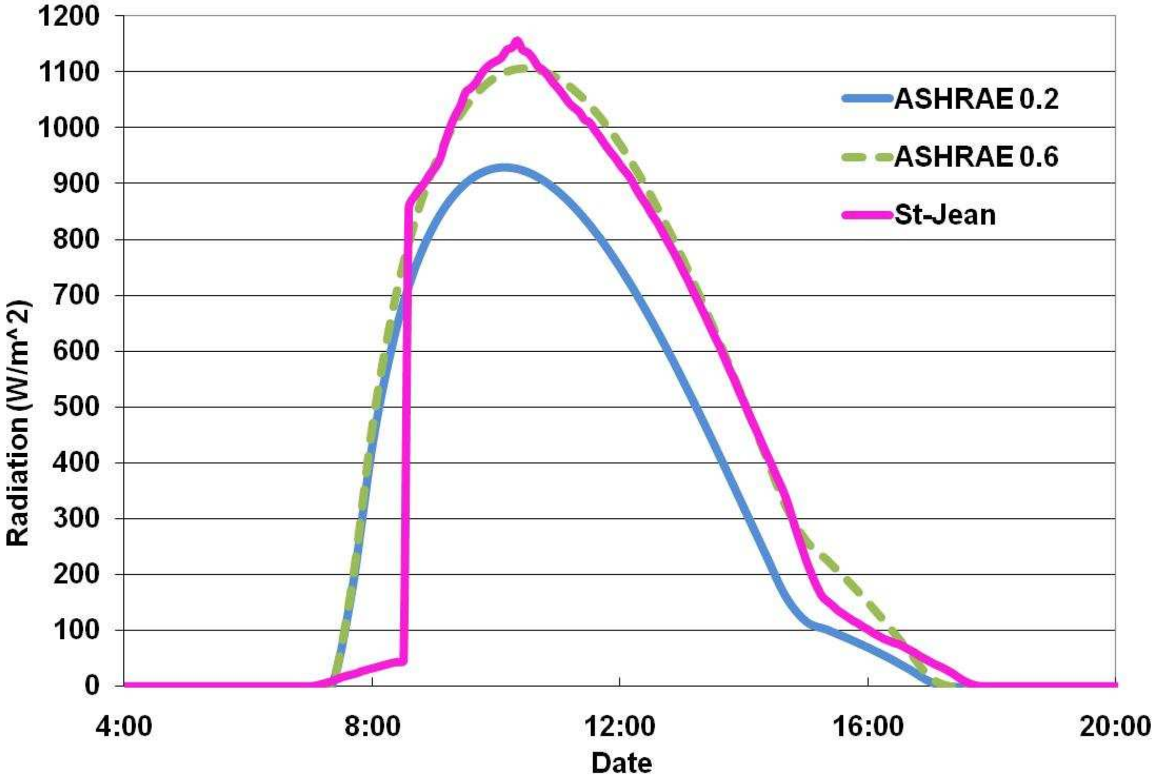

Figure 5.10: Comparison between the vertical absorbed solar radiation values measured by the vertical Hobo silicon pyranometer radiation sensor used on the experimental site (Latitude 45.5°), on February 14th, 2009 and that calculated using Equation (15); for the ground reflection factor ρ_g, a value of 0.6 rather than 0.2, produces values corresponding more closely to those measured by the vertical sensor after 3:00 pm when the incident solar radiation is mainly reflected and diffused. Before 9:00 am, the low absorbed radiation results from the experimental barn shadow effect on the vertical sensor.

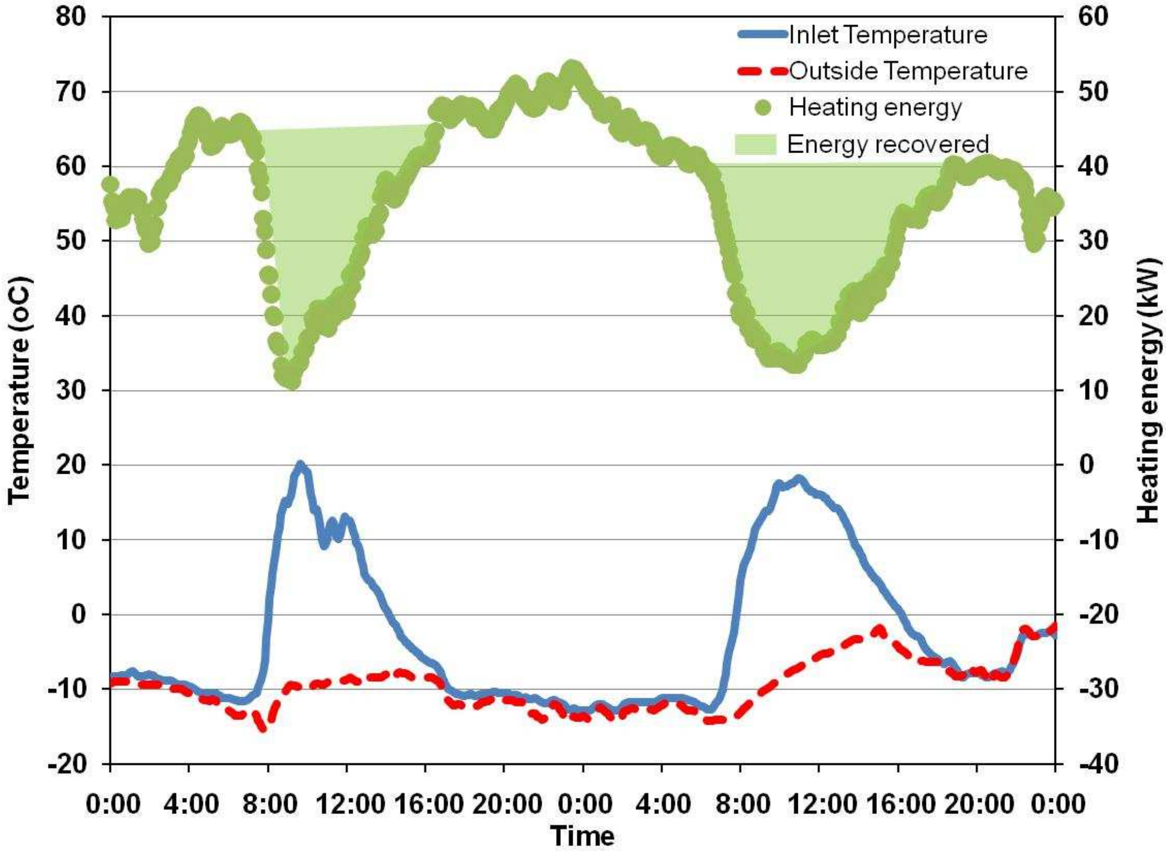

Figure 5.11: Saving in heating load as the solar air pre-heaters recover energy and increase the temperature of the incoming fresh air, on February 24th and 25th, 2009. On each respective day, the solar air pre-heaters saved 432 and 540 MJ in heating load.

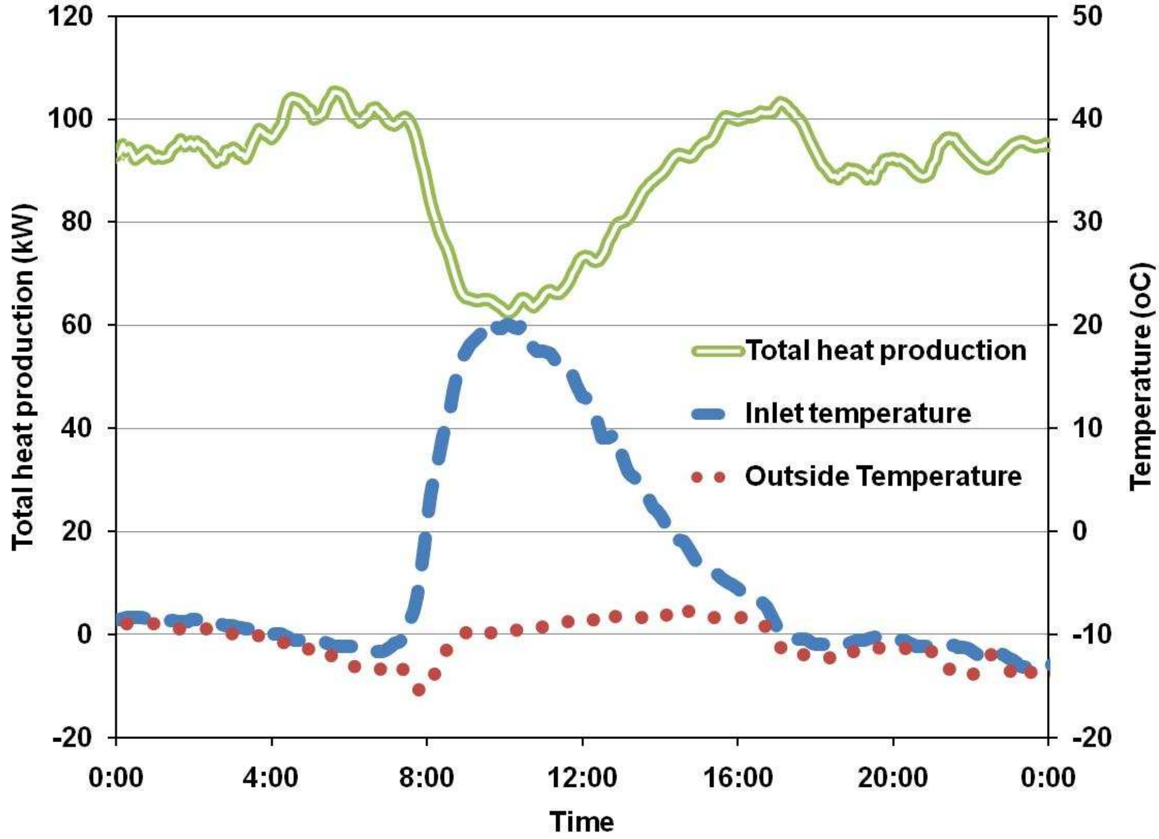

Figure 5.12: Calculated bird latent and sensible heat production (S_s + S_l) during a typical sunny day (February 25th) when the solar air pre-heaters increase the inlet air temperature by 30°C. Such an event leads to fresh air short-circuiting towards and a drop in air temperature at exhaust fans, as demonstrated by a drop in the calculated (S_s + S_l) value.

Chapter 6: General Conclusion

As fossil fuel consumption continues to fulfill world energy need, there will be a pressure on the development of more efficient renewable energy sources. Agriculture is able to produce several sources of renewable energy such as biomass. One promising renewable energy source in agriculture is solar power, such as the solar air heater. The proven technology of the unglazed transpired plate in the commercial and industrial sector has been newly introduced to the agricultural sector.

To estimate the profitability in term of fuel saving as well as the environmental impact, an evaluation of the energy efficiency of the solar air collector as been made on two commercial boilers barns. The solar air heater from November to March had efficiency varying from 35% to 64% with measurement sensors having a maximum error of 6%. Results show that the lower is radiation level, the higher is the efficiency. Wind velocity plays also an important role in the energy efficiency, as well as the energy recovery. This wind effect occurs when the solar air heater is not design properly with the proper flow rate and dimensions. Average daily efficiency can be as high as 65% when wind velocity is below 2 m/s and it can be as low as 25% when wind is blowing with velocities exceeding 7m/s. Assuming a CAN$ 0.08/kWh for the natural gas energy cost, the annual return on investment is 4.7% with an annual energy recovery representing CAN$14.80 per square meter of solar air heater.

A heat balance was conducted to measure bird heat production under field conditions. An evaluation was also been made to find impacts of ventilation air solar heaters on heat load and bird performance as well as an identification of strategies to reduce winter heating load has been performed. The data collected for chicken heat production corresponded to those measured under laboratory conditions. The heat balance showed that air stratification was created inside barns and it was the main source of heat loss (about 30%). Using a ventilation system with a capacity to circulate the air inside the room is recommended. Results showed that the heating load is reduced with the use of the solar air heater and it is also possible, when the heaters are not in use, that the ventilation rate can increase and provide a better air quality inside without any additional cost.

An evaluation of the data acquisition system installed to conduct the energy balance was completed to find the right strategy to better monitor an agricultural livestock building. It was found that the ambient air temperature was one of the hardest parameters to monitor when temperature stratification occured. During the energy balances studies, air temperature stratification was the key component leading to high heat losses caused by a lack of air mixing. Because the inside air relative humidity varies with temperature, temperature sensors should be all combined sensors to measure also relative humidity. Ventilation rate can be adequately measured by using an electromagnetic device that monitored fan rpm. Nevertheless, air flow through fans can change according to outside wind velocity and maintenance activities. Radiation measurements of the absorbed direct, diffused and reflected radiation were made using pyranometers. Even if they were accurate, they need regular calibration based on manufacturer's recommendations. All improvements on the acquisition system will lead to a better understanding of the poultry environment and then, to a better management causing an increase in the energy efficiency of the agricultural buildings and a decrease in the production costs.

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