Energies **2013**, *6*, 184-203; doi:10.3390/en6010184

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Experimental Study of a Triple Concentric Tube Heat Exchanger Integrated into a Wood-Based Air-Heating System for Energy-Efficient Dwellings

Pierre Peigné [1], Christian Inard [2,*] and Lionel Druette [1]

[1] CERIC Laboratory (Centre d'Essais et de Recherche des Industries de la Cheminée), Poujoulat Group, 79270 Saint-Symphorien, France ; E-Mails: p.peigne@laboratoire-ceric.com (P.P.); l.druette@laboratoire-ceric.com (L.D.)

[2] LaSIE (Laboratoire des Sciences de l'Ingénieur pour l'Environnement), Department of Civil Engineering, University of La Rochelle, 17042 La Rochelle, France

* Author to whom correspondence should be addressed; E-Mail: christian.inard@univ-lr.fr; Tel.: +33-054-645-7246; Fax: +33-054-645-8241.

Received: 30 October 2012; in revised form: 18 December 2012 / Accepted: 21 December 2012 / Published: 8 January 2013

Abstract: In this paper, experimental tests conducted on a new wood-based air-heating system for energy-efficient dwellings are presented. The main objective is to evaluate the resulting outlet temperatures and the amount of heat recovered by the ventilation air in order to assess feasibility and performance of coupling a mechanical ventilation heat-recovery unit and a triple concentric tube heat exchanger integrated into the chimney of a room-sealed wood-pellet stove to heat an entire house. After introducing the context of this work, the three main components of the combined system developed here, the coupling configuration adopted, as well as the protocol used and the sensors implemented on an experimental setup carried out in a laboratory are detailed in turn. Then, the heat transfer rates obtained from measurements for the various fluids as well as the effectiveness of the heat exchangers are presented and discussed. Finally, the resulting outlet temperatures of the three fluids exchanging in the triple concentric tube heat exchanger studied here are compared to those provided by analytical solutions obtained with a mathematical model. It is shown that heat transfer rates are predicted with a relative difference that is lower than 5% compared to experimental values and that such a system enables to cover all or most of heat losses in an energy efficient building.

Keywords: low energy building; air heating system; wood pellet stove; heat recovery ventilation; triple concentric tube heat exchanger; experiments

Nomenclature:

c_p	specific heat capacity at constant pressure (J/(kg·K))
C	heat capacity rate (J/K)
E	effectiveness or efficiency (%)
E'	improved effectiveness or efficiency (%)
P_E	electrical power (W)
P_T	thermal power (W)
q_m	mass flow rate (kg/s)
S	section area (m^2)
T	temperature (K)
v	velocity (m/s)
z	heat capacity rate ratio (min/max) (-)

Greek Symbols

ε_r	relative difference between computed and experimental results (%)
ϕ	heat flow rate (W)
ρ	density (kg/m^3)
ΔX	absolute uncertainty of parameter X (unity of X)
$\Delta X/X$	relative uncertainty of parameter X (%)

Subscripts

comp	computed
exp	experimental
in	inlet
out	outlet
max	maximum
min	minimum
pellet	pellet

Acronyms

CA	combustion air
EA	exhaust air
FA	fresh air
FG	flue gases
OUT	outside
TOT	total
VA	ventilation air
MVHR	mechanical ventilation heat recovery
RSWPS	room-sealed wood pellet stove

TCTHE	triple concentric tube heat exchanger
TCTHE-NI	triple concentric tube heat exchanger with no insulation

1. Introduction

Since the building sector accounts for almost a third of final energy consumption globally and is an equally important source of CO_2 emissions, energy efficient dwellings and their dedicated equipment are advocated by governments as suitable solutions to contribute in meeting a part of the current energy and environmental issues [1,2] while ensuring the comfort of the inhabitants. Indeed, these constructions are both highly insulated and sealed, so the fresh air needs can neither be provided by air leakage in the building envelope, nor by uncontrolled air flow rates from natural ventilation. Thus, mechanical ventilation is certainly the only way to supply filtered fresh air with controlled air change rates in tightly air sealed buildings in order to protect people from unhealthy indoor pollutants and odours.

Moreover, high efficiency heat recovery ventilation units lead to very low demand for heating and cooling in these buildings [3]. For example, in passive houses, remaining energy demand becomes low enough to be provided by a controlled unit at about 0.4 air changes per hour to fulfill sufficient indoor air quality conditions with no recirculated air [4]. In this way, it is fundamental that all ventilation ducts are insulated and sealed against leakage. In addition, a maximum supply air temperature of 50 °C is applied to prevent any possible smell of scorching from dust [5]. Thus, mechanical ventilation heat recovery (MVHR) systems, with a heat recovery rate of over 80% and high-efficiency electronically commutated motors, are often employed to maintain air quality and to recover sufficient heat to dispense with a conventional central heating system. However, if MVHR systems can give substantial final energy reduction, the primary energy benefit depends strongly on the type of heat supply system [6].

In the same time, policies promote the development and the optimization of new energy production sources based on the use of renewable energy. Thus, with respect to wood energy, biomass action plan [7] has been implemented to comply with the European commission directives on the energy performance of buildings [8] and on the promotion of energy from renewable sources [9], which aims to achieve 20% of gross energy consumption from renewable sources by 2020. According to the Joint Wood Energy Enquiry [10] cited by the European Forestry Commission [11], the annual growth of wood energy is about 3.5% in recent years to account for 50% of renewable energy sources in the twelve European countries that responded to the enquiry. In particular, private households appear to be the largest users of wood energy and this situation is expected to continue through the structuring of the sector, the development of efficient appliances and a supportive regulatory environment.

In this context, an effective way to cover the remaining heating loads in energy efficient dwellings is the use of small wood-burning appliances for example [12–14]. As such, wood pellet stoves appear to be well suited because they have a variable heating rate control and wood pellet is a highly efficient combustible which is easier to store than wood logs and stacks, mainly due to the 15 kg packaging. Moreover, compared to other fuels, wood pellets have a lower heating value (LHV) which is higher than 5 kWh/kg and a low ash production. In addition, the charm of the dancing flames behind the glass of the unit makes this type of device particularly attractive. However, it is advised to choose a very low power device [12–15], with a maximum heating power of about 5 or 10 kW in energy efficient houses and only about 1 or 2 kW in passive houses. Indeed, as the stove is usually placed in a central position in the house, usually the living room, the kitchen or the hall, and as its operation is generally controlled only by this room temperature, the heat release should be prolonged whether by a large thermal mass or by a good air circulation between the zones [15]. In practice, the wood pellet stoves are often coupled to the domestic hot water storage or to a hot air distribution system in order to limit the temperature differences between parts of the house and prevent overheating of the room where the appliance is installed.

Moreover, despite the fact that there is no obvious relationship between the presence of a wood-burning appliance and respiratory health risk for occupants [16], it must be underlined that conventional warm air distribution systems collect heat by drawing air above the heater device, which can increase diffusion of dust in the house or even of contaminants if the appliance is not maintained or used properly [17].

As a consequence, a combined system has been developed to uniform temperature in energy efficient dwellings heated by a wood pellet stove and ventilated by a mechanical system with heat recovery. In this work, the solution proposed is to recover heat from flue gases by blowing the major part of the ventilation air flow in a specific heat exchanger integrated into the chimney of the pellet stove in order to distribute it in other rooms by using the ventilation air supply network.

2. Combined System Description

In the combined system studied here, the mechanical ventilation with heat recovery (MVHR) is coupled with a room-sealed wood pellet stove (RSWPS) thanks to a triple concentric tube heat exchanger (TCTHE). These three main components are presented in Figure 1.

Figure 1. View of the three main components of the combined system.

2.1. Mechanical Ventilation Heat Recovery (MVHR)

The MVHR used in this study is the model AKOR-HR manufactured by UNELVENT (Thuir, France) and designed for domestic dwellings. It is a high quality product easy to use and maintain. It has also been proven by many years of use and optimization. This device contains a counter current heat exchanger with efficiency up to 90%, two low power direct current fans with a maximum electrical consumption of 195 W each and two G3 air filters upstream of the heat exchanger. This unit can provide an air flow rate of 200 m^3/h with 150 Pa pressure drop in the duct network and an electrical power lower than 100W. Automatically, a bypass ensures summer comfort in the house and an ambient air intake valve enables the unit defrost. The device has also a remote control with three speeds of operation: low for absence, normal when busy and high if activity. The high speed may be set for 10, 20 or 30 min. All ventilation ducts are rigid metal pipes with smooth interior walls to minimize head losses.

2.2. Room Sealed Wood Pellet Stove (RSWPS)

The RSWPS used in this work is the model ELENA NEW manufactured by PALAZZETTI (Porcia, Italy). Fully automatic and programmable, this appliance is certified [18] for the sealing of its combustion circuit, meaning that the rate of air leakage from the wood stove is lower than the regulatory requirements [19,20]. Indeed, the manufacturer devoted one’s whole attention to the combustion chamber, the glass, the hopper and the auger mechanism, to reach a high degree of air tightness. Thus, the operation of the RSWPS does not interfere with the ventilation system and there is no risk of flue gas backflow into the house. In France, installation of sealed combustion appliances enables to respect regulatory texts for the prevention of poisoning by carbon monoxide in the premises of housing [21], as well as for the implementing rules in terms of technical requirements for ventilation, exhaust of the combustion products, and maintenance of the heating device [22].

The nominal power of the appliance model ELENA NEW is close to 9 kW and its combustion efficiency is above 80%. Both nozzles for the exhaust of flue gases and the intake of combustion air are in diameter 80 mm. A similar energy consumption but 6 kW nominal power device (3 kW minimum power), model called ELENA MINI, is recently available to better meet the needs of small buildings with very low energy consumption. This model is more efficient than the one used in this study since its combustion efficiency is equal to 94.5%. Nevertheless, this model was not available during this study. User can continuously monitor and display the operating power of the stove (from P1 to P5 or Automatic) the speed of the fan blowing warm air (from V1 to V5 or Automatic) and the setpoint for ambient temperature in the living room (from 10 to 40 °C or High).

2.3. Triple Concentric Tube Heat Exchanger (TCTHE)

First and foremost, the TCTHE developed in this study is a static component integrated into the chimney of a RSWPS in order to warm up all of part of the ventilation air which is supplied in the house by a MVHR.

As shown in Figure 2, the chimney of a RSWPS is often composed of concentric elements that ensure both flue gases evacuation and combustion air admission. Thus, flue gases are evacuated through the inner tube and the combustion air is brought down through the annular space between the inner tube and the outer tube of diameter 80 mm and 130 mm respectively. Accordingly, the sealing of construction is preserved and the ventilation system is not disturbed. In addition, the combustion air is heated in the annular space along the entire length of the chimney and so combustion efficiency can be improved by around 10% and carbon emissions are reduced thanks to better combustion [23].

As depicted in Figure 3, the TCTHE consists of two parts, each having a side opening of 125 mm diameter for either the entry or exit of the ventilation air. In this study, the inlet and outlet of the ventilation air are located on the upper part and lower part of the heat exchanger respectively. By this way, flue gases and vent air are in a counter-current flow arrangement, so that a maximum of heat is transferred. Of course, the inlet and outlet of the ventilation air could be reversed if necessary.

Figure 2. Diagram of a concentric element of the chimney of the wood pellet stove.

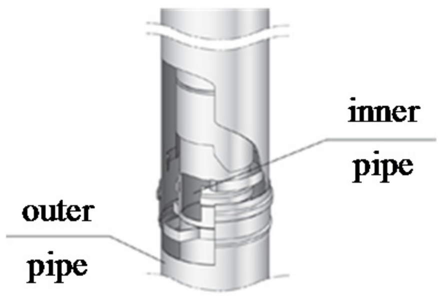
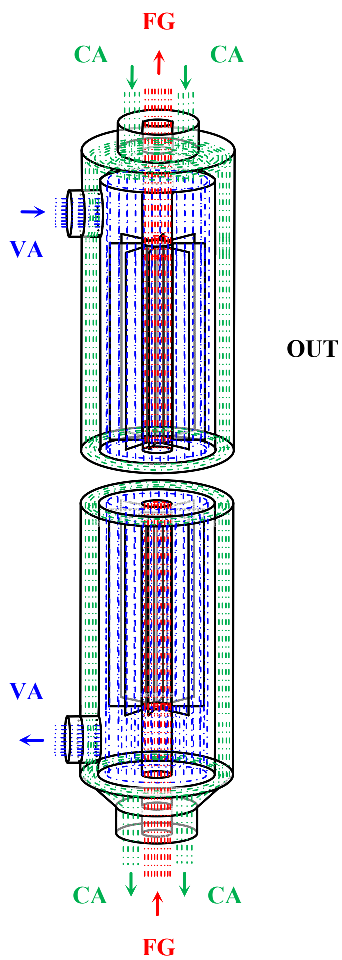


Figure 3. Diagram of the TCTHE.



To clarify the flow pattern of the three gases within the TCTHE, the flue gases (FG) are evacuated through the inner tube, the ventilation air (VA) is heated from top to bottom between the inner tube and the intermediate tube, and the combustion air (CA) which ensures the correct operation of the wood pellet stove is brought down between the intermediate tube and the outer tube. As a consequence, the flue gases and ventilation air are in a counter-flow arrangement, while the ventilation air and combustion air are in a parallel-flow arrangement. It should also be noted that this component is not insulated from the outside (OUT). Thus, heat transfer also occurs between combustion air and ambient air.

With a total height of 1945 mm, the TCTHE is made of three concentric stainless steel tubes of 0.4 mm thickness. The diameters of the three tubes are 80 mm, 180 mm and 230 mm, respectively. While limiting the size of the installation, these dimensions allow to integrate the heat exchanger with the concentric elements forming the chimney, but also to lead to minimum head losses for each fluid. Indeed, tests were conducted to quantify the pressure drop in annular flow areas. Thus, the head losses in the ventilation flow area air are below 50 Pa for a flow rate of 250 m^3/h and the values obtained in the combustion air flow area remain below 5 Pa for a flow rate of 30 m^3/h.

Then, eight stainless steel fins of 1280 mm height, 45 mm width and 0.4 mm thick, are welded outside the inner tube to enhance the exchange on the ventilation air side. Thermal joints are used to seal perfectly the upper and lower parts of the heat exchanger. Moreover, as ventilation air is pulsed into the heat exchanger, any risk of discharge of flue gases or combustion air in the ventilation air flow area is avoided.

Nevertheless, leak tests were performed on the TCTHE for the three flow areas of fluids. The measured leak rate corresponds to the amount of compressed air being supplied to maintain a differential pressure of 200 Pa between the inlet and outlet of the tested area. The results obtained are 0.7, 1.8 and 40.0 L/h respectively for the flue gases, the ventilation air and the combustion air. Leakage rates achieved for flue gases and ventilation air are very low and reflect the great tightness of the first two concentric tubes. The leak rate measured for the combustion air is more important because the outer wall of the exchanger consists of several parts welded together. Nevertheless, the depression in the combustion air flow area is only about 10 Pa in actual conditions. Moreover, it should be emphasized that the system works by blowing ventilation air in the triple concentric tube heat exchanger, so there is no risk of system malfunction or contamination of ventilation air.

2.4. Coupling Configuration

The ideal configuration should combine all the advantages of the RSWPS and the MVHR while also introducing the TCTHE to better distribute heat in the house. As the flue gases temperature decreases gradually through the chimney, the TCTHE should be installed closest to the pellet stove.

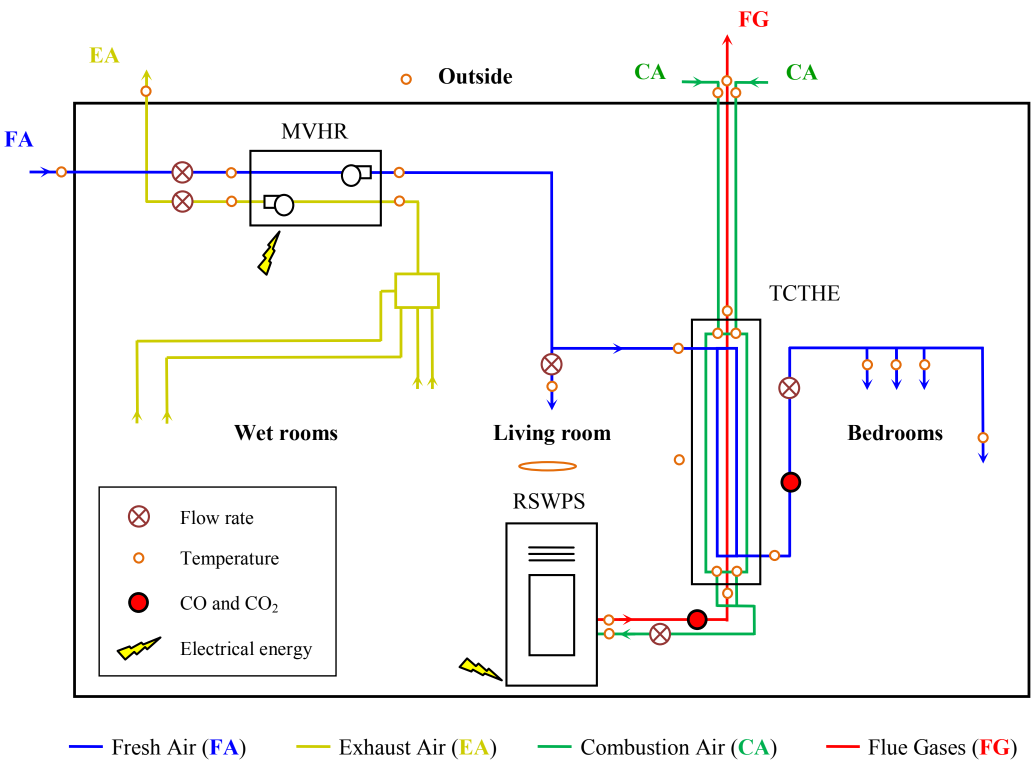
Moreover, as the TCTHE is connected to ventilation ducts, it should be hidden in a dedicated closet located just behind the stove. This place should also be kept easily accessible to perform the various necessary maintenance operations, such as the chimney sweeping or the removing of any possible condensation. With an outer diameter of 230 mm for the TCTHE and by taking into account the space required for the connection of ventilation ducts, dimensions of the closet should be at least 0.5 m long and 0.5 m large over the entire height of the room.

Then, the MVHR unit has to be located upstream of the TCTHE. Indeed, it's the only possible configuration to blow ventilation air in the annular space between flue gases and combustion air in order to ensure system security. It should also be noted that there is no recirculation of air in this system. Hence, the supply air is only a fresh air. Another advantage consists of the implement of the MVHR unit in an equipment room located directly above the closet containing the TCTHE in order to limit the total head loss in the ventilation network.

A part of ventilation air should also be blown into the living room immediately after passing through the MVHR unit. Obviously, as the wood pellet stove is located in this room, there is no need of additional heat at this place. Then, insulation of all ducts is recommended to limit heat losses.

Considering all the above, the authors recommend to combine the three main components of the system as it is shown in Figure 4 in order to uniform temperatures in the best way throughout the house and prevent any risk of ventilation air contamination by the combustion products.

Figure 4. Scheme of the system configuration and implementation of sensors.



3. Experimental Setup in Laboratory

The experimental setup has been achieved in the first half of 2010 at the premises of the Research and Testing Centre for the Chimney and Flue Industry (CERIC laboratory). This installation was conducted to assess feasibility and performance of the ventilation and wood-based air heating system described in detail in the previous sections.

3.1. Instrumentation

While implementation of the sensors is already depicted in Figure 4, Table 1 outlines the main characteristics of the temperature and flow sensors. Air and combustion analyzers are also used to measure CO and CO_2 rates on the ventilation air downstream the heat exchanger and on flue gases, respectively. Electrical power meters are also set up at the RSWPS and the MVHR.

Table 1. Applications and characteristics of the temperature and flow sensors used on the experimental setup.

Quantity and type of sensors used	Accuracy and range of reliability after calibration		Fluid(s) measured
12 thermocouples type T (copper-constantan)	±0.06 °C	0 to 100 °C	combustion air
12 thermocouples type K (chromel-alumel)	±0.20 °C	0 to 250 °C	flue gases
30 thermocouples type K (chromel-alumel)	±0.06 °C	0 to 100 °C	ventilation, ambient, external air
1 vane wheel flow sensor (stainless steel)	±0.10 m/s	0 to 5 m/s	flue gases
1 vane wheel flow sensor (aluminium)	±0.10 m/s	0 to 5 m/s	ventilation air in the TCTHE
1 thermal flow sensor (thin-film element)	±0.05 m/s	0 to 2 m/s	combustion air
2 thermal flow sensors (thin-film element)	±0.10 m/s	0 to 5 m/s	fresh air and exhaust air
1 air velocity transducer (omnidirectional)	± 0.10 m/s	0 to 5 m/s	supply air in the living room

Figure 5 gives an overall view of the combined system installation in CERIC laboratory. The closet behind the stove is open only for the need of the photography. Arrows indicate the nature of the various fluids in the system.

Figure 5. View of the experimental setup in laboratory.

3.2. Protocol

Tests are performed for the three main operating modes of the RSWPS (P1-V1 ≡ 3.5 kW, P3-V3 ≡ 6.7 kW, P5-V5 ≡ 9.6 kW) and for the three main operating speeds of the MVHR (Low ≡ 80 m^3/h, Normal ≡ 115 m^3/h, High ≡ 180 m^3/h). Such flow rates allow to ensure the renewal and quality of indoor air in dwellings with about 100 m^2 living space occupied by 4 inhabitants, in accordance with French guidelines [24].

As a little part of fresh air is directly blown into the living room after the MVHR unit, most of the fresh air is blown into the TCTHE. Therefore, the ventilation air flow rate in the TCTHE is 65 m^3/h, 85 m^3/h or 130 m^3/h, when the operating speed of the MVHR unit is respectively low, normal or high.

Measurements are recorded every 10 s by a datalogger. The steady state is reached about half an hour after starting the wood pellet stove. The running averages of temperature and flow rate measurements are then stored to carry out heat balances.

Density ρ and specific heat c_p of the ventilation air and combustion air are calculated using correlations obtained from the table values of thermo-physical properties of dry air between 250 K and 400 K at atmospheric pressure [25]. The standard NF EN 13384-1 [26] is used to calculate the density and specific heat of the flue gases.

According to the NF EN 14785 [27], the combustion efficiency of the stove E_{RSWPS} is evaluated from carbon contents in flue gases, *i.e.*, CO and CO_2 concentrations, and from the temperature difference $\Delta T_{\text{FG-CA}}$ between the exit of flue gases and entrance of combustion air at the back side of the RSWPS. In addition, losses due to unburned fuel are assumed to be about 2% for wood pellets.

The mass flow rate of pellet being burnt $q_{m\,\text{pellet}}$ is also evaluated for the various heating rates of the stove and the lower heating value (LHV) of the wood pellets used during the tests is 19,782 kJ/kg. Thus, the maximum thermal power that could be released from the amount of pellet being burnt $P_{T\,\text{pellet}}$ is given by:

$$P_{T\,\text{pellet}} = \frac{19782}{3.6} q_{m\,\text{pellet}} \tag{1}$$

and the thermal power delivered by the stove into the living room $P_{T\,\text{RSWPS}}$ is expressed as:

$$P_{T\,\text{RSWPS}} = E_{\text{RSWPS}}\, P_{T\,\text{pellet}} \tag{2}$$

The thermal power carried by flue gases $P_{T\,\text{FG}}$ can also be deducted as:

$$P_{T\,\text{FG}} = (0.98 - E_{\text{RSWPS}})\, P_{T\,\text{pellet}} \tag{3}$$

Then, temperature and flow sensors are set up to measure the heat flow rates transferred inside the TCTHE and the MVHR. The heat transfer rates are evaluated for the three fluids (FG, VA and CA) exchanging into the TCTHE, as well as for the fresh air (FA) and the exhaust air (EA) flowing in the ventilation unit. The heat transfer rate ϕ_i assigned or retrieved by the fluid i is expressed in terms of density ρ_i in the section S_i where velocity v_i is measured, average specific heat c_{pi} of the fluid and temperature difference ($T_{i\,\text{out}} - T_{i\,\text{in}}$) between the outlet and the inlet of the exchanger, as:

$$\phi_i = \rho_i\, v_i\, c_{p\,i}\, S_i\, (T_{i\,\text{out}} - T_{i\,\text{in}}) = C_i\, (T_{i\,\text{out}} - T_{i\,\text{in}}) \tag{4}$$

where $C_i = \rho_i v_i c_{pi} S_i$ is the heat capacity rate of the fluid i.

Within the triple concentric tube heat exchanger with no insulation at the outer surface (TCTHE-NI) whose mathematical model is presented in [28], the heat balance could be written as follows:

$$\phi_{\text{FG}} + \phi_{\text{CA}} = \phi_{\text{VA}} + \phi_{\text{OUT}} \tag{5}$$

where ϕ_{FG} is the heat transferred from the flue gases to the ventilation air, ϕ_{CA} is the heat transferred from the combustion air to the ventilation air and the ambient air at the outside, ϕ_{VA} is the heat recovered from the ventilation air and ϕ_{OUT} is the heat recovered from the ambient air at the outside.

As the goal of the TCTHE-NI is to recover heat on ventilation air flowing in an annulus between flue gases and combustion air, as well as considering that in any case $C_{VA} \geq C_{FG} + C_{CA}$, the expression of the heat exchanger effectiveness $E_{TCTHE\text{-}NI}$ is found [28] to be written as:

$$E_{\text{TCTHE-NI}} = \frac{C_{\text{VA}}\ (T_{\text{VA out}} - T_{\text{VA in}})}{C_{\text{FG}}\ (T_{\text{FG in}} - T_{\text{VA in}}) + C_{\text{CA}}\ (T_{\text{CA in}} - T_{\text{VA in}})} \tag{6}$$

and could be represented graphically in function of the non-dimensional parameter z_{TCTHE} defined as the ratio of the minimum heat capacity rate to the maximum heat capacity rate:

$$z_{\text{TCTHE-NI}} = C_{\min} / C_{\max} = (C_{\text{FG}} + C_{\text{CA}}) / C_{\text{VA}} \tag{7}$$

Similarly, considering that in any case $C_{FA} \leq C_{EA}$, the effectiveness of the MVHR unit is given by:

$$E_{\text{MVHR}} = \frac{C_{\text{FA}}\ (T_{\text{FA out}} - T_{\text{FA in}})}{C_{\text{EA}}\ (T_{\text{EA in}} - T_{\text{FA in}})} = z_{\text{MVHR}} \frac{(T_{\text{FA out}} - T_{\text{FA in}})}{(T_{\text{EA in}} - T_{\text{FA in}})} \tag{8}$$

with the non-dimensional parameter $z_{MVHR} = C_{min}/C_{max} = C_{FA}/C_{EA}$.

Considering that absolute and relative uncertainties of parameter X measurement are noted ΔX and $\Delta X/X$ respectively, the relative uncertainty of heat transferred by the fluid i is given by:

$$\frac{\Delta \phi_i}{\phi_i} = \frac{\Delta C_i}{C_i} + 2\frac{\Delta T_i}{T_i} \qquad \forall i \in \{1,2,3\} \equiv \{\text{FG}, \text{VA}, \text{CA}\} \tag{9}$$

The relative uncertainty of the effectiveness is obtained from the following expressions for the TCTHE-NI and the MVHR unit:

$$\frac{\Delta E_{\text{TCTHE-NI}}}{E_{\text{TCTHE-NI}}} = \frac{\Delta C_{\text{FG}}}{C_{\text{FG}}} + \frac{\Delta C_{\text{CA}}}{C_{\text{CA}}} + \frac{\Delta C_{\text{VA}}}{C_{\text{VA}}} + \frac{\Delta T_{\text{FG}}}{T_{\text{FG}}} + \frac{\Delta T_{\text{CA}}}{T_{\text{CA}}} + 4\frac{\Delta T_{\text{VA}}}{T_{\text{VA}}} \tag{10}$$

$$\frac{\Delta E_{\text{MVHR}}}{E_{\text{MVHR}}} = \frac{\Delta C_{\text{EA}}}{C_{\text{EA}}} + \frac{\Delta C_{\text{FA}}}{C_{\text{FA}}} + \frac{\Delta T_{\text{EA}}}{T_{\text{EA}}} + 3\frac{\Delta T_{\text{FA}}}{T_{\text{FA}}} \tag{11}$$

3.3. Results

In this section, the combustion analysis of the wood pellet stove and measurements of electrical power are first presented. Then, heat transfer rates within the TCTHE-NI and the MVHR unit, as well as the heat exchangers effectiveness are given with their measurement uncertainty. The temperature differences of each fluid between inlets and outlets of both heat exchangers are also presented. Finally, the experimental results obtained for the TCTHE-NI are compared with those computed using a mathematical model [28], and the relative difference between experimental and numerical values is stated and discussed.

3.3.1. Combustion Analysis

First of all, concentrations of CO and CO_2 in the ventilation air flowing downstream the heat exchanger have been recorded continuously during all the experiments. As the CO concentration remains below 1.5 ppm and the CO_2 concentration ranges from 400 ppm to 500 ppm, conclusion is there is no contamination of the ventilation air by the combustion products. Table 2 gives measurements and computed results from the combustion analysis of the RSWPS. For the sake of clarity, temperatures values as well as CO and CO_2 concentrations are rounded to the nearest unit, while computed thermal powers $P_{T\,\mathrm{pellet}}$, $P_{T\,\mathrm{RSWPS}}$ and $P_{T\,\mathrm{FG}}$ are rounded to the nearest half-ten.

The efficiency of the RSWPS is around 80% and increases slightly when the operating mode increases. As announced by the manufacturer, the thermal power delivered by the wood pellet stove is between 3.5 kW and 9.6 kW. The thermal power carried by the flue gases is then between 800 W at P1-V1 and 1680 W at P5-V5.

As discussed at the end of this study, if some part of the thermal power carried by the flue gases is recovered by the ventilation air within the TCTHE-NI, this heat recovering could be considered as an improvement of the heating device efficiency.

Table 2. Results of the combustion analysis of the RSWPS.

Parameters	Units	P1-V1	P3-V3	P5-V5
T_{FG}	°C	205	270	320
T_{CA}	°C	50	60	70
CO_2	%	5	8	11
CO	ppm	125	50	100
$q_{m\,\mathrm{pellet}}$	kg/h	0.8	1.5	2.1
E_{RSWPS}	%	79.7	81.9	83.4
$P_{T\,\mathrm{pellet}}$	W	4400	8240	11540
$P_{T\,\mathrm{RSWPS}}$	W	3505	6750	9625
$P_{T\,\mathrm{FG}}$	W	805	1325	1685

3.3.2. Electrical Power

Table 3 gives the electrical power used by the RSWPS and the MVHR unit for each operating mode and speed used during the experimental study. It should also be noted that the wood pellet stove needs about 400 W during the 10 min of its ignition phase and about 60 W during the 15 min of its extinction phase, but its standby power consumption never exceed 5 W.

Table 3. Electrical power used by the RSWPS and the MVHR.

RSWPS operating mode	P1-V1	P3-V3	P5-V5
$P_{E\,\mathrm{RSWPS}}$ (W)	35	55	80
MVHR operating speed	**Low**	**Normal**	**High**
$P_{E\,\mathrm{MVHR}}$ (W)	15	25	40

3.3.3. Heat Transferred and Effectiveness

Table 4 gives the heat transfer rates obtained from the temperature and flow rate measurements for each fluid in the TCTHE-NI and the MVHR unit. The non dimensional parameter z and the heat exchanger effectiveness E are also given.

Globally, the heat recovered by the ventilation air ϕ_{VA} within the TCTHE is very slightly influenced by the operation speed of the MVHR unit. In contrast, the operating modes of the RSWPS are well identified and the average amount of heat recovered by the ventilation air is about 350 W at P1-V1, 550 W at P3-V3 and 700 W at P5-V5, when the ventilation operation speed is normal. Thus, recovered heat by the ventilation air is about two times higher at maximum operating mode P5-V5 than at minimum operating mode P1-V1. Regarding MVHR unit, the heat recovered by all the fresh air ϕ_{FA} is mainly influenced by the speed of operation of ventilation, with about 250 W, 350 W and 600 W respectively when speed is low, normal and high.

As expected, heat transfer mainly occurs between the flue gases and the ventilation air through the inner tube wall. But it may be noted that the heat released by the combustion air ϕ_{CA} remains very low with only about 50 W at P1-V1, 60 W at P3-V3 and 100 W at P5-V5. Since the temperature in the technical closet containing the TCTHE-NI is between 28 and 35 °C during all the experiments, the heat transferred from the combustion air to the external environment ϕ_{OUT} is very low, 14 W and 63 W respectively. In this study, insulation of the TCTHE-NI does not appear to be justified in comparison with the increased costs it entails.

Table 4. Heat transfer rates and effectiveness within the TCTHE-NI and the MVHR unit.

EXP data	**MVHR**	**High**			**Normal**			**Low**		
	RSWPS	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5
TCTHE-NI	ϕ_{FG} (W)	325	511	692	320	496	658	294	474	619
	ϕ_{VA} (W)	361	560	745	349	539	706	320	515	655
	ϕ_{CA} (W)	50	81	106	47	78	105	44	74	99
	ϕ_{OUT} (W)	14	32	52	18	35	57	18	34	63
	$z_{TCTHE\text{-}NI}$ (-)	0.28	0.32	0.37	0.43	0.51	0.56	0.60	0.69	0.79
	$E_{TCTHE\text{-}NI}$ (%)	29.5	29.3	27.6	28.3	26.7	26.3	26.8	25.8	24.4
MVHR	ϕ_{FA} (W)	533	581	770	318	324	414	221	231	275
	ϕ_{EA} (W)	507	564	744	300	325	414	208	218	274
	z_{MVHR} (-)	0.79	0.81	0.82	0.94	0.94	0.96	0.99	0.93	0.94
	E_{MVHR} (%)	93.2	92.0	91.7	90.0	86.7	86.9	88.2	90.6	88.7

It is also worth noting that the amounts of heat recovered by the ventilation air in the TCTHE-NI and by the fresh air in the MVHR unit are substantially equivalent, but effectiveness is between 25% and 30% for the TCTHE-NI and is between 85% and 95% for the MVHR unit. However, the effectiveness of the TCTHE-NI is adequate to heat the ventilation air without affecting the proper discharge of flue gases, which remains the primary objective of the chimney.

3.3.4. Temperatures

The values of each fluid temperature at the inlets and outlets of the two heat exchangers namely TCTHE-NI and MVHR are given in Table 5. While in the TCTHE-NI, the inlet temperature of the combustion air is systematically higher than the inlet temperature of the ventilation air, bold values show that the outlet temperature of the ventilation air becomes higher than the outlet temperature of the combustion air, except when the MVHR unit operating speed is high. This temperature cross phenomenon reflects the reversal of heat exchanges from a certain point in the TCTHE-NI. Thus, for the low and normal operating speeds of the MVHR unit, there is a place on the height of the heat exchanger where the heat flux initially transferred from the combustion air to the ventilation air is reversed and heat is transferred from the ventilation air to the combustion air.

It is also worth mentioning that the temperature difference of the ventilation air between the inlet and outlet of TCTHE-NI is between 10 °C and 30 °C, while the fresh air temperature increase is only between 10 °C and 15 °C in the MVHR.

Table 5. Inlet and outlet temperatures of each fluid within the TCTHE-NI and the MVHR unit.

EXP	**MVHR**	**High**			**Normal**			**Low**		
data	RSWPS	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5
TCTHE-NI	$T_{FG\ in}$ (°C)	175.9	237.7	285.9	176.2	236.5	282.4	171.3	237.5	278.5
	$T_{FG\ out}$ (°C)	133.0	176.9	214.9	134.2	180.7	214.9	132.2	183.4	215.3
	$T_{VA\ in}$ (°C)	25.6	27.6	29.2	26.1	27.0	28.9	24.6	27.3	27.1
	$T_{VA\ out}$ (°C)	34.5	41.7	48.3	**39.1**	**47.6**	**56.1**	**41.4**	**54.3**	**62.1**
	$T_{CA\ in}$ (°C)	47.5	60.5	70.0	48.9	60.8	71.7	47.4	62.4	70.9
	$T_{CA\ out}$ (°C)	35.0	42.0	48.4	**37.1**	**43.4**	**50.3**	**36.2**	**45.8**	**50.9**
	T_{OUT} (°C)	29.6	32.9	34.9	30.2	31.5	34.4	28.3	32.5	32.9
MVHR	$T_{FA\ in}$ (°C)	15.9	17.1	15.6	17.2	17.8	17.5	15.9	18.4	16.5
	$T_{FA\ out}$ (°C)	25.6	27.5	29.1	25.9	26.8	28.6	24.4	27.0	26.7
	$T_{EA\ in}$ (°C)	26.3	28.4	30.3	26.9	28.1	30.3	25.6	28.6	28.8
	$T_{EA\ out}$ (°C)	19.0	20.3	19.6	19.2	19.7	19.6	17.7	19.8	17.9

3.3.5. Measurements Uncertainty

As shown in Table 6 for the TCTHE-NI, the relative uncertainty of the heat recovered by the ventilation air $\Delta\phi / \phi_{VA}$ is below 10.1%, while the relative uncertainty of the effectiveness $\Delta E/E_{TCTHE\text{-}NI}$ reaches 28.6% due to the calculation involving the sum of relative uncertainty of the heat capacity rates and temperature differences for each fluid. It could be noticed that the largest measurement uncertainties are those of the mass flow rates, in particular for the flue gases.

Table 6. Relative uncertainty of heat transfer rates and effectiveness within the TCTHE-NI and the MVHR unit.

EXP	**MVHR**	**High**			**Normal**			**Low**		
data	RSWPS	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5
TCTHE-NI	$\Delta\phi / \phi_{FG}$ (%)	10.8	9.7	8.9	10.8	9.5	8.9	11.0	9.6	8.9
	$\Delta\phi / \phi_{VA}$ (%)	7.4	6.4	5.9	8.4	7.7	7.3	10.1	9.4	9.1
	$\Delta\phi / \phi_{CA}$ (%)	7.7	6.7	6.3	7.8	6.7	6.3	7.9	6.8	6.3
	$\Delta E/E_{TCTHE\text{-}NI}$ (%)	26.9	23.3	21.3	27.0	23.8	22.3	28.6	25.3	24.0
MVHR	$\Delta\phi / \phi_{FA}$ (%)	6.1	5.9	5.4	6.9	6.8	6.2	7.5	7.4	6.9
	$\Delta\phi / \phi_{EA}$ (%)	6.8	6.4	5.7	7.1	6.8	6.2	7.5	7.3	6.8
	$\Delta E/E_{MVHR}$ (%)	12.5	12.1	10.9	13.8	13.6	12.4	14.9	14.7	13.7

3.3.6. Comparison with Numerical Results

Since the geometrical parameters of the TCTHE-NI are known and presented in Section 2.3, the measurement of inlet temperatures and mass flow rates of each fluid gives the set of input data used in the mathematical model that is developed in [28].

Considering that the effective length of the TCTHE-NI where the three fluids are truly in a counter-co-current flow arrangement is 1650 mm, and that eight fins are welded on the outer wall of the inner tube, calculations are conducted to determine the outlet temperatures and the transferred heat for each fluid within the TCTHE-NI, and then the effectiveness of the exchange is evaluated.

Table 7 gives the computed results of the amounts of heat transferred by each fluid within the TCTHE-NI, as well as the overall effectiveness of the heat exchanger.

Table 7. Computed results of heat transfer rates and effectiveness within the TCTHE-NI.

COMP	**MVHR**	**High**			**Normal**			**Low**		
data	RSWPS	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5
TCTHE-NI	ϕ_{FG} (W)	329	503	687	317	500	652	295	480	624
	ϕ_{VA} (W)	359	549	746	342	538	701	314	511	662
	ϕ_{CA} (W)	50	81	109	48	79	106	44	74	99
	ϕ_{OUT} (W)	20	35	50	23	41	56	25	44	60
	$E_{TCTHE\text{-}NI}$ (%)	29.3	28.7	27.7	27.7	26.6	26.2	26.4	25.5	24.7

As shown in Figure 6, the computed heat transfer rates of each fluid in the TCTHE-NI are in good agreements with values obtained from the experimental measurements for the various operating modes of the RSWPS and the various operating speeds of the MVHR unit.

Figure 6. Experimental and computed values of heat transfer rates within the TCTHE-NI.

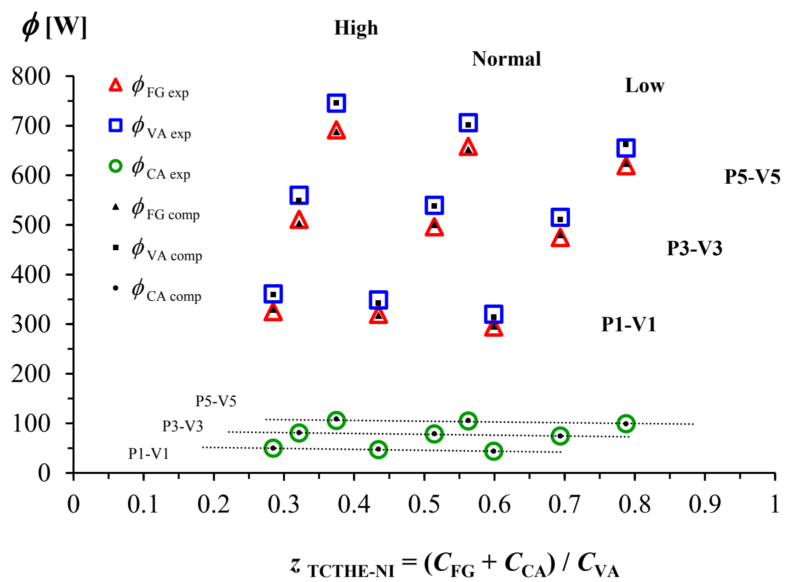


Figure 7 shows that computed and experimental values of the TCTHE-NI effectiveness are in good agreements with a relative difference which remains below 2% for the various operating modes of the RSWPS and the various operating speeds of the MVHR unit. A trend line connects the TCTHE-NI effectiveness values obtained from experimental measurements and their relative uncertainties are depicted by curves in dotted lines.

Figure 7. Experimental and computed values of the TCTHE-NI effectiveness.

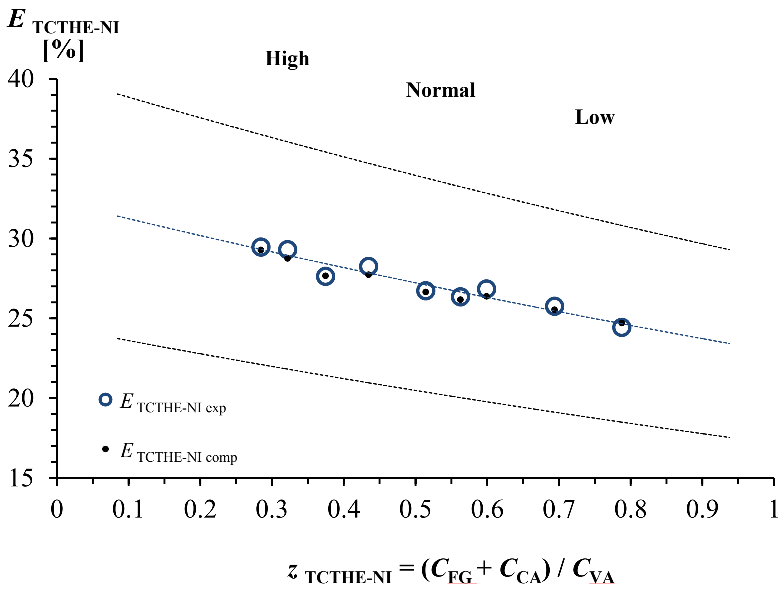


Table 8 gives the relative differences ε_r between the values of heat transfer rates obtained from computations and experiments. They are below 1.6%, 1.9% and 2.8% for the flue gases, the ventilation and the combustion air, respectively. As for the effectiveness of the TCTHE-NI, the relative differences between the computed and experimental values are similar to those obtained for the heat transfer rate of the ventilation air due to the effectiveness expression given by Equation (6), where only the outlet temperature of the ventilation is not part of the set of input parameters of the mathematical model. Furthermore, as the heat transfer rate from the combustion air to the outside was not measured during the experiments but only computed using the heat balance given by Equation (5), the relative differences between computed and experimental values of the amount of heat transferred to the external environment of the TCTHE-NI cannot be given.

Table 8. Relative differences between experimental and computed results within the TCTHE-NI.

COMP	MVHR	High			Normal			Low		
data	RSWPS	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5	P1-V1	P3-V3	P5-V5
TCTHE-NI	$\varepsilon_{r\phi\,\mathrm{FG}}$ (%)	1.3%	1.6%	0.6%	0.7%	0.7%	1.0%	0.4%	1.1%	0.7%
	$\varepsilon_{r\phi\,\mathrm{VA}}$ (%)	0.6%	1.9%	0.1%	1.9%	0.3%	0.7%	1.7%	0.9%	1.1%
	$\varepsilon_{r\phi\,\mathrm{CA}}$ (%)	0.03%	0.8%	2.8%	1.8%	0.4%	1.0%	0.1%	0.4%	0.3%
	$\varepsilon_{r\,E\,\mathrm{TCTHE\text{-}NI}}$ (%)	0.6%	1.9%	0.1%	1.9%	0.3%	0.7%	1.7%	0.9%	1.1%

Finally, the good agreement between the computed and experimental results provides the validation of the mathematical model presented in [28] and the analytical solutions used to assess the outlet temperature of each fluid enable predicting performances of the TCTHE-NI accurately.

3.3.7. RSWPS Efficiency Improvement

Adding the heat recovered by the ventilation air within the TCTHE-NI for normal operating speed of the MVHR unit with the amount of heat delivered in the room where the wood-burning appliance is located enables to propose a new formulation of the RSWPS efficiency, which is given by the following expression:

$$E'_{\text{RSWPS}} = (P_{T\,\text{RSWPS}} + \phi_{\text{VA TCTHE-NI}}) / P_{T\,\text{pellet}} \quad (12)$$

The new values of the RSWPS efficiency given in the last row in Table 9 are increased by a minimum of 6.1% and a maximum of 7.7% compared to the previous ones given in Table 2.

Table 9. Values of the RSWPS efficiency including heat recovered by the TCTHE-NI.

Parameters	Units	P1-V1	P3-V3	P5-V5
E_{RSWPS}	%	79.7	81.9	83.4
$P_{T\,\text{pellet}}$	W	4400	8240	11540
$P_{T\,\text{RSWPS}}$	W	3505	6750	9625
$P_{T\,\text{FG}}$	W	805	1325	1685
$\phi_{\text{VA TCTHE-NI}}$	W	340	540	700
E'_{RSWPS}	%	87.4	88.5	89.5

4. Conclusions

An innovative wood-based air-heating system has been developed thanks to the design of a triple concentric tube heat exchanger integrated into the chimney of a room sealed wood pellet stove and linked to the mechanical ventilation heat recovery network.

The experimental study conducted in laboratory demonstrates the feasibility, reliability and performance of the combined system. In the configuration adopted, whole or part of the fresh ventilation air can pass through the TCTHE located downstream of the MVHR unit. Furthermore, the combined system benefits are both the filtration and flow rate control performed by the MVHR unit. Then, the sealing of the three flow areas in the TCTHE is checked, as well as the head losses introduced into the ventilation network. The amount of heat recovered by the ventilation air within the TCTHE is around 500 W at the intermediate operating mode of the RSWPS and at the normal operating speed of the MVHR, which is enough to uniform temperature in the rooms and to cover all or most of heat losses in an energy efficient dwelling.

As the heat transferred to the external environment of the TCTHE-NI remains low, it is found that the insulation of the TCTHE is not justified with respect to the increased costs it entails. Moreover, the good agreement between computed and experimental results of heat transfer rates and effectiveness within the TCTHE-NI supports the interest of using a mathematical model to predict its performance with accuracy.

To conclude, the TCTHE-NI is a static component which enables coupling a RSWPS with a MVHR unit in order to distribute heat power in the whole house and achieve a better thermal comfort while ensuring occupants safety, indoor air quality and improving the combustion efficiency of the wood-burning appliance. This combined system is installed in two monitored low energy houses with a living area of 100 m² since September 2010 and first results presented and discussed in [28] assess its feasibility and performance as well as inhabitants satisfaction. In addition, a comparison between energy consumption of apartments equipped with the proposed system and another without will be carrying out including control of the system. This will be the subject of another article. Finally, since experimental and numerical results are in a good agreement, the next step will consist to implement the mathematical model of the TCTHE-NI inside a dynamic thermal simulation code for buildings.

Acknowledgments

This work was supported in part by the Poitou-Charentes Regional Council and by the Calyxis cluster of expertise in risk.

References

1. International Energy Agency (IEA). *Technology Roadmap—Energy Efficient Buildings: Heating and Cooling Equipment*. Available online: http://www.iea.org/publications/freepublications/publication/buildings_roadmap-1.pdf (accessed on 1 October 2012).
2. European Commission (EC). *Action Plan for Energy Efficiency: Realising the Potential*. Available online: http://eur-lex.europa.eu/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumber&lg=en&type_doc=COMfinal&an_doc=2006&nu_doc=545 (accessed on 1 October 2012).
3. Plateforme de Recherche et d'Expérimentation sur l'Énergie dans le Bâtiment (PREBAT). *International Building and Energy Comparison—Final Report*; PREBAT: Paris, France, 2007.
4. Feist, W. *Passive House: Learn the Basic Knowledge. Definition of Passive Houses. Heating with Nothing Other Than Fresh Air*; Passivhaus Institut: Darmstadt, Germany, 2006.
5. Fraefel, R.; Huber H.; Trawnika M. *L'Aération dans les Bâtiments MINERGIE—Guide de Conception*; Clima Suisse: Zürich, Switzerland, 2000.
6. Dodoo, A.; Gustavsson, L.; Sathre, R. Primary energy implications of ventilation heat recovery in residential buildings. *Energy Build.* **2011**, *43*, 1566–1572.
7. European Commission (EC). *Communication on the Biomass Action Plan*; Office for Official Publications of the European Communities: Brussels, Belgium, 2005.
8. European Commission (EC). *Directive 2002/91/EC on the Energy Performance of Buildings*; Office for Official Publications of the European Communities: Brussels, Belgium, 2003.
9. European Commission (EC). *Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC* (Text with EEA relevance); Office for Official Publications of the European Communities: Brussels, Belgium, 2009.

10. Steierer, F.; Fischer-Ankern, A. *Wood Energy in Europe and North America: A New Estimate of Volumes and Flow*; Joint Wood Energy Enquiry Report; 6 February 2007. Available online: http://staging.unece.org/fileadmin/DAM/timber/docs/stats-sessions/stats-29/english/report-conclusions-2007-03.pdf (accessed on 1 October 2012).
11. Food and Agriculture Organization (FAO). *Wood Energy for Europe: Status and Outlook*. Available online: http://www.fao.org/docrep/meeting/018/k7431e.pdf (accessed on 1 October 2012).
12. Feist, W.; Schnieders, J.; Dorer, V.; Haas, A. Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy Build.* **2005**, *37*, 1186–1203.
13. Pfluger, R. Wood stoves in passive houses—Strategies for comfort. In *Proceedings of the 12th International Conference on Passive House*, Nuremberg, Germany, 11–12 April 2008.
14. Persson, T.; Nordlander, S.; Rönnelid, M. Electrical savings by use of wood pellet stoves and solar heating systems in electrically heated single-family houses. *Energy Build.* **2005**, *37*, 920–929.
15. Hastings, S.R. Breaking the "heating barrier": Learning from the first houses without conventional heating. *Energy Build.***2004**, *36*, 373–380.
16. Lévesque, B.; Allaire, S.; Gauvin, D.; Koutrakis, P.; Gingras, S.; Rhainds, M.; Prud'Homme, H.; Duchesne, J.F. Wood-burning appliances and indoor air quality. *Sci. Total Environ.* **2001**, *281*, 47–62.
17. Consumer Safety Commission. *Recommendation on Hot Air Redistribution Systems*. Available online: http://www.securiteconso.org/article230.html (accessed on 16 September 2012).
18. Centre Scientifique et Technique du Bâtiment (CSTB). *Avis Technique 14/08-1276 Palazzetti*. Available online: http://www.cstb.fr/pdf/atec/GS14-O/AO081276.pdf (accessed on 5 October 2012).
19. *NF EN 613/A1-2003 Appareils de Chauffage Indépendants à Convection Utilisant les Combustibles Gazeux*; Association Française de Normalisation (AFNOR): Saint-Denis, France, 2003.
20. *PrEN 16510-1 Residential Solid Fuel Burning Appliances—Part 1: General Requirements and Test Methods*; Draft Standard from CEN/TC295/WG3, 2012.
21. Journal Officiel de la République Française (JORF). *Decree No. 2008-1231 of November 27, 2008 on the Prevention of Poisoning by Carbon Monoxide*. Available online: http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000019830531&dateTexte=&categorieLien=id (accessed on 9 October 2012).
22. Journal Officiel de la République Française (JORF). *Order of February 23, 2009 Taken for the Application of Articles R. 131-31 to R. 131-37 of the Code of Construction and Housing on the Prevention of Poisoning by Carbon Monoxide in the Premises for Residential Use*. Available online: http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000020314838&dateTexte=&categorieLien=id (accessed on 9 October 2012).
23. Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME); Centre d'Essais et de Recherche des Industries de la Cheminée (CERIC); Laboratoire National d'Essais et de métrologie (LNE); Technova. *Influence of Metallic Chimney Flue on the Performance of Residential Wood Burning Appliance*, 2009. Available online: http://www.laboratoire-ceric.fr/pdf/Influence_conduit.pdf (accessed on 5 October 2012).

24. Journal Officiel de la République Française (JORF). *Arrêté du 24 Mars 1982, Modifié par L'arrêté du 28 Octobre 1983, Relatif à L'aération des Logements: Aération Générale ou Permanente, Aération Permanente Pouvant Être Limitée à Certaines Pièces*. Available online: http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=LEGITEXT000006074206&dateTexte=20100319 (accessed on 9 October 2012).
25. Incropera, F.P.; de Witt, D.P.; Bergman, T.L.; Lavine, A.S. *Fundamentals of Heat and Mass Transfer*, 6th ed.; Wiley: New York, NY, USA, 2006.
26. *NF EN 13384-1+A2 Août 2008 Conduits de Fumée—Méthodes de Calcul Thermo-Aéraulique—Partie 1: Conduits de Fumée ne Desservant qu'un Seul Appareil*; Association Française de Normalisation (AFNOR): Saint-Denis, France, 2008.
27. *NF EN 14785 Août 2006 Appareils de Chauffage Domestique à Convection à Granulés de Bois—Exigences et Méthodes d'Essai*; Association Française de Normalisation (AFNOR): Saint-Denis, France, 2006.
28. Peigné P. Étude d'un Système Combiné de Ventilation et de Chauffage au Bois dans les Bâtiments à Basse Consommation d'Énergie. Ph.D. Thesis, Université La Rochelle, La Rochelle, France, 2012.