Design, Efficiency and Recovered Energy of an Air-to-Air Energy Recovery System for Building Applications in Hot-Humid Climate

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Abstract: ***Recently, concerns on energy consumption and air quality in buildings have significantly increased. Hence, a system namely "air-to-air energy recovery" has been introduced to overcome this problem. It functions to pre-heat and/or pre-cool the incoming air by using the outgoing air and simultaneously provides healthy fresh air to indoor spaces. The application of this system has widely been used in countries that experience cold climates. However, only a few studies present scientific works pertaining to hot-humid climate zone in open literature. To close this gap, thus this study presents a work on an air-to-air energy recovery system for building applications in hot-humid climate. The objective of this study was to evaluate the efficiency and recovered energy of the system. Experimental investigations were conducted under controlled conditions in Energy and IEQ Testing Unit located in School of Industrial Technology, Universiti Sains Malaysia. Tests were carried out under different airflow rates ranged from 1.0 to 3.0 m/s and intake air temperature of 31℃, 35℃ and 40℃. The efficiency and recovered energy of the system were calculated and evaluated by adopting calculation method by ASHRAE Standard. The efficiency of this system ranged from 45 to 85 % and the highest recovered energy of 17.5 kW was achieved at 1.0 m/s and 31℃. From these results, it was found that the efficiency decreased and in contrast the recovered energy increased with increasing airflow rates.***

Keywords: Air-to-air energy recovery, Efficiency, Recovered energy

1. Introduction

Total energy consumption of buildings accounts for significant percentages of national energy consumption worldwide. According to IEA [1] buildings represent about 40% of primary energy consumption in most countries. The major energy consumption in buildings are heating, cooling and air-conditioning (HVAC) systems. Liu et al. [2] stated that space heating is the most important building energy consumer in cold countries, whereas air-conditioning is a major contributor to peak electricity demand in hot-humid climate countries or during summer. These HVAC systems will continue to take a large proportion of total energy consumption in buildings as reported in [3]. Therefore, if targets for energy reduction in buildings are to be met, it is essential that technologies to reduce energy consumption are designed to have the maximum impact of energy saving.

With the growing concern of buildings require a source of fresh air and energy reduction, air-to-air energy recovery system appears as one of the key solutions to generate energy saving [4]. The air-to-air energy recovery system, also known as energy recovery ventilator or heat recovery is a mechanical system that removes stale, polluted air from indoor spaces and replaces it with fresh outdoor air. Besides, the system involves a process of recovering energy (heat and/or mass) from a stream at a high temperature to a low temperature stream through a heat exchanger to maintain a comfortable temperature of indoor spaces [2]. In other words, in this system, the energy that would otherwise be lost is used to heat the air in cooler stream - helps to recover a part of energy loss. Routlet et al. [5] and Zhang et al. [6] reported that the system also can be operated as a ventilation system in summer or hot season and cost effective. Therefore, more and more air handling units are equipped with energy recovery technologies with the aim of decreasing the energy consumption in buildings in the current years [7] and [8]. In conserving energy, the system pass the warm air from one stream (warm) to the other stream (cool) through an internal component which is the heat exchanger where heat transfer occurs. Typically, the system has the capability to recover about 60-95% of heat in exhaust stream [4]. Min and Su [9] in their paper had explained about a basic physical model of air-to-air energy recovery system and its components, which makes it unique in its operation and behaviour. As a whole, the system varies according to its type, size and flow arrangement as discussed in [10], [11], [12], [13], [14] and [15].

To date, as reported in [10] many studies have been conducted on air-to-air energy recovery systems for building applications. Some of the findings are reported in [16], [17], [18], [19], [20] [21], [22], [23], [24]. Only a few studies provide scientific works on the air-to-air energy recovery systems in relation to climate zones. For instance, Zhong and Kang [25] analysed the role of the air-to-air energy recovery systems in reducing energy consumption in four different climate zones in China. On the other hand, Fehrm et al. [26] performed a research on the application of air-to-air energy recovery system in Europe, particularly for cold climate. Delfani et al. [7] and [27] studied about air-to-air energy recovery system for building applications in various climates of Iran.

Despite the enormous number of research devoted to the system since 1980s [28], little attention has been paid on the performance in terms of efficiency and energy load for building applications in hot-humid climate zone, at least in open literature. To narrow this gap, this study proposed a design of an air-to-air energy recovery system for potential application in hot-humid climate. Efficiency and recovered energy were investigated and evaluated using experimental approach.

2. Design and System Description

The air-to-air energy recovery system in this study was designed to recover energy in hot-humid climate with the design parameters of: i) airflow ranged from 300 to 60,000m^3/h; ii) intake temperatures ranged from 30 to 45 °C; room temperatures ranged from 20 to 25°C. In this system, the air-to-air energy recovery core was formed based on hydrophilic polymeric membrane layers, impregnated with unique ingredients and addictive and structured with 23 pieces of waveform stand or sinusoidal plate-fin channels. The membrane layers were arranged in a cross-flow manner and have the capabilities to transfer both heat and moisture simultaneously. This configuration also allowed air to change direction in a manner that ensures sufficient air comes in contact with heat transfer surface prior leaving the core (airflow of 300 to 60,000 m^3/h). The dimensions of the core were 0.2 m height, 0.2 m length and 0.1 m width with 0.002 m height of sinusoidal plate fin channels. A core shell was designed to house the core at the centre with two separate flexible air ducts (intake and exhaust) (Figure 1). The shell was made of 0.025 m thick polystyrene sandwich panels with thin aluminium sheet for insulation purpose. Each duct has a diameter of 0.015 m. The shell helped to station and separate two airstreams (intake and exhaust) of the core. Two DC centrifugal fans with maximum of 24 V were installed in the intake and exhaust ducts to assist airflow and distribute the air through the air-to-air energy recovery system.

3. Experimental Set Up and Procedure

A series of experimental investigation was conducted under laboratory conditions in Energy and IEQ Testing Unit located in School of Industrial Technology, Universiti Sains Malaysia. Figure 2 illustrates the experimental set up of the system. The air-to-air energy recovery system was tested in a controlled experimental chamber that includes a room (R) with a dimension of 2.9 m x 4.6 m x 5 m, an insulated test room (TR) with a dimension of 2 m x 2 m x 2 m and air-to-air energy recovery system

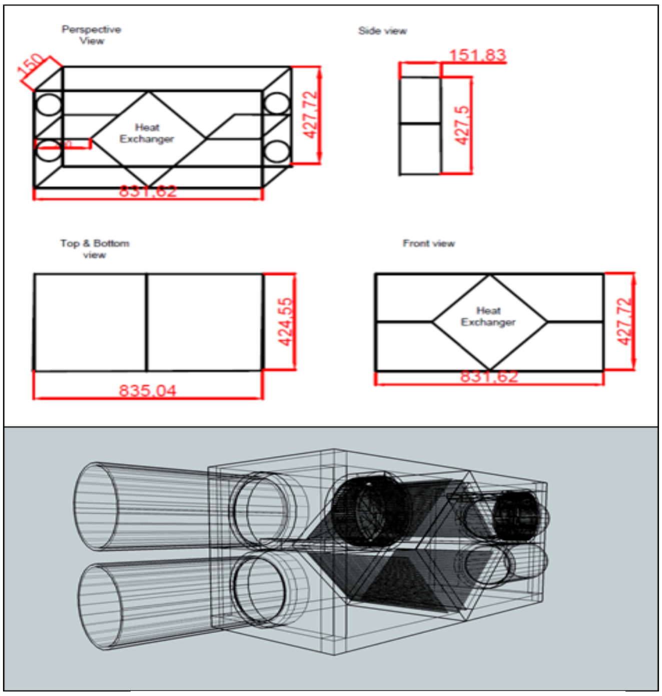

Figure 1: Design of air-to-air energy recovery system

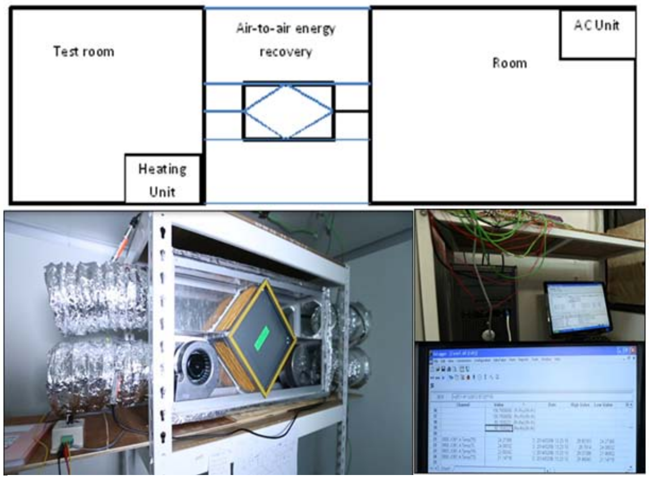

Figure 2: Experimental set up of air-to-air energy recovery system in Energy & IEQ Testing Unit

The test room was made of 0.045 m polyurethane foam sandwich panel to reduce the effect of surroundings. The test room was used as a controlled chamber to regulate hot temperatures between 30 and 45 °C. An artificial heating system was used to generate heat in the test room. Meanwhile, an air-conditioning equipment was placed to simulate cold temperature in the room. Measurements were carried out under different airflow rates ranged from 1.0 to 3.0 m/s using established method by Fisk et al. [29] as stated in [30]. In order to test the efficiency of the system at different airflows, two speed controllers were connected to the DC centrifugal fans. Intake air temperature before entering core (T_i), intake air temperature after entering core (T_s), return air temperature (T_r) and exhaust air temperature after entering core (T_e) were recorded using type-K thermocouple (+/- 2.2^{0}C or +/- 75%) and were placed at 16 different points across the experimental chamber. Four thermocouples were placed in the test room (TR) and five thermocouples were placed in the room (R). For airflow measurements, a hot-wire anemometer (±3% of reading, ±0.05m/s) was used to measure airflow rates of intake and exhaust airstreams at the same points of temperature measurement. Log-Tchebycheff method was applied in order to obtain accurate airflow rate values [31].

For each test, the experimental chamber was allowed to come to steady state condition which was achieved after 45 minutes. The measurements were carried out after the experimental chamber reached steady state conditions using data acquisition system comprising DT800 with DeLogger™ 5 Pro Software. Data were collected over a period of 2 h for each test. Results were analysed to evaluate the efficiency and recovered energy of the system. The tests were carried out at mean room temperature of 24 °C and mean intake temperature (T_i) of 31 ^{0}C, 35 ^{0}C and 40 ^{0}C. Efficiency ($\mathcal{E}_{ER}$) and recovered energy (Q_{ER}) of the system were then calculated and tabulated at different airflow rates by adopting calculation method as suggested by ASHRAE Standard [14], [30] and [32].

4. Results and Discussion

4.1 Airflow rate and temperature data

Table 1, 2 and 3 show the measured and calculated data of the air-to-air energy recovery system at mean intake temperature (T_i) 31 ^{0}C, 35 ^{0}C and 40 ^{0}C, respectively for airflow rate ranged from 1.0 to 3.0 m/s (0.018 – 0.054 m^3/s). From this data it was calculated that the temperature difference (ΔT) at intake temperature 31 ^{0}C was 3.53 °C, at 35 ^{0}C was 8.91 °C and at 40 ^{0}C was 14.02 °C for airflow rate of 1.0 m/s (0.018 m^3/s). On the other hand, at airflow rate 3.0 m/s (0.054 m^3/s), ΔT was found to be in a range of 4.15 to 9.71 °C.

Table 1: Measured and calculated data at 31 ^{0}C

Intake air velocity, V_i (m/s)	Volumetric airflow rate, Q_i (m^3/s)	Mass air flow rate, M_a (kg/s)	T_i (^{0}C)	T_s (^{0}C)	T_r (^{0}C)	T_e (^{0}C)
1.0	0.018	0.021	31.08	27.55	25.36	30.14
1.5	0.027	0.031	31.07	27.48	24.68	31.48
2.0	0.036	0.042	31.20	27.77	25.18	31.12
2.5	0.045	0.052	31.09	26.54	22.88	32.02
3.0	0.054	0.063	30.90	26.75	23.89	30.00

Table 2: Measured and calculated data at 35 ^{0}C

Intake air velocity, V_i (m/s)	Volumetric airflow rate, Q_i (m^3/s)	Mass air flow rate, M_a (kg/s)	T_i (^{0}C)	T_s (^{0}C)	T_r (^{0}C)	T_e (^{0}C)
1.0	0.018	0.021	34.97	26.06	23.58	33.84
1.5	0.027	0.031	35.08	28.88	25.15	35.17
2.0	0.036	0.041	35.07	28.94	25.27	34.73
2.5	0.045	0.052	35.14	28.43	23.17	36.95
3.0	0.054	0.062	35.08	29.83	25.98	34.53

Table 3: Measured and calculated data at 40 ^{0}C

Intake air velocity, V_i (m/s)	Volumetric airflow rate, Q_i (m^3/s)	Mass air flow rate, M_a (kg/s)	T_i (^{0}C)	T_s (^{0}C)	T_r (^{0}C)	T_e (^{0}C)
1.0	0.018	0.020	40.07	26.05	23.66	36.80
1.5	0.027	0.030	39.94	29.83	25.39	39.38
2.0	0.036	0.041	40.14	30.42	26.48	39.23
2.5	0.045	0.051	40.15	30.16	23.19	42.99
3.0	0.054	0.061	40.04	30.33	26.06	39.18

4.2 Efficiency of the system

Figure 3 illustrates the efficiencies of the system based on the measured for airflow rates (V_i) ranged from 1.0 to 3.0 m/s (Q_i = 0.018 to 0.054 m^3/s) and tested intake temperatures (T_i) of 31 ^{0}C, 35 ^{0}C and 40 ^{0}C. From the figure, it can be seen efficiency increased with increasing airflow rates for every tested temperature. The relationship between efficiency and airflow rates at 31 ^{0}C, 35 ^{0}C and 40 ^{0}C can be expressed by Equation 1, 2 and 3, respectively.

$$y = -2.7x + 65.9 \text{ – Equation 1}$$

$$y = -4.9x + 78.5 \text{ – Equation 2}$$

$$y = -9.3x + 93.9 \text{ – Equation 3}$$

This trend can be explained by a theory of residence time within the air-to-air energy recovery core, which is the average amount of time that a substance (air) spends in the core. The higher the residence time, the higher is the effectiveness [31]. In contrast, efficiency decreased with increasing intake temperature. The efficiency ranged from 45 to 85%. The highest efficiency (85%) was achieved at (0.018 m^3/s) and 40 ^{0}C. Meanwhile, the lower temperature was achieved at (0.054 m^3/s) and 40 ^{0}C. Thus, intake air conditions give significant effects to the performance in terms of efficiency of energy recovery system as suggested in [33].

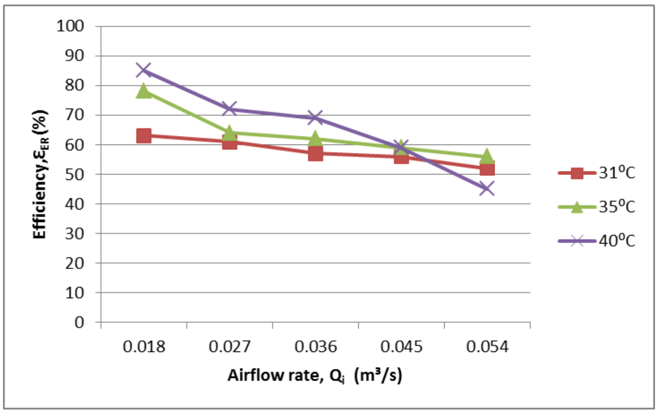

Figure 3: Efficiency of the system versus airflow rate

4.3 Recovered energy of the system

The variations of recovered energy with airflow rates are shown in Figure 4 for airflow rates (V_i) ranged from 1.0 to 3.0 m/s and tested intake temperature (T_i) of 31 ^{0}C, 35 ^{0}C and 40 ^{0}C. From the study it was found that the recovered energy of air-to-air energy recovery system increased with increasing airflow rates. The highest recovered energy of 17.50 kW was achieved at 3.0 m/s and the lowest was achieved at 1.0 m/s for intake air temperature of 31 ^{0}C. Whilst, for intake air temperature of 40 ^{0}C, the lowest recovered energy of 5.77 kW was obtained at 1.0 m/s and the highest was obtained at 3.0 m/s.

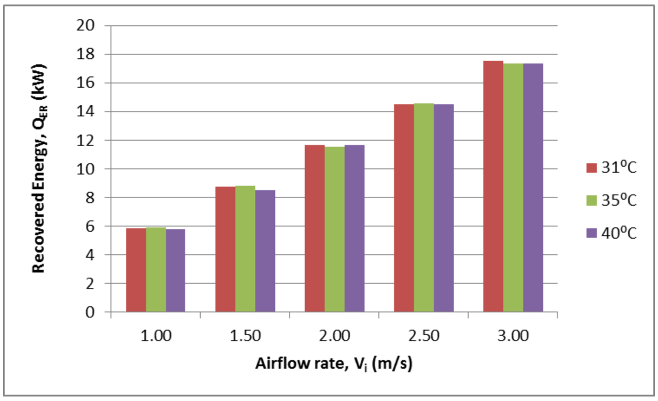

Figure 4: Recovered energy of the system

5. Conclusion

An air-to-air energy recovery system was completely designed and tested to evaluate the efficiency and recovered energy of the system for building applications in hot-humid climate. In order to achieve its objectives, a series of experimental investigations were carried out at room temperature of 24 °C and intake temperature (T_i) of 31 ^{0}C, 35 ^{0}C and 40 ^{0}C in School of Industrial Technology, Universiti Sains Malaysia. It was found that the efficiency of the system decreased with increasing airflow rates. Meanwhile, when the airflow rate increased, the recovered energy increased. The efficiency of the system ranged from 45 to 85 % with the highest recovered energy of 17.50 kW. Thus, as a conclusion, the efficiency and recovered energy of the system were affected by the intake air conditions. A thorough study on thermal performance of the system should be further investigated in relation to sensible and latent loads as well as effects of various operating parameters.

6. Future Scope

There are several directions where the current research work can be extended. A thorough study on thermal performance of the system should be further investigated in relation to sensible and latent loads as well as effects of various operating parameters. In addition, field testing and practical application of the system on real existing buildings should also be carried out in the future.

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