Energy xxx (2018) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Mixed numerical - Experimental approach to enhance the heat pump performance by drain water heat recovery

Mohamad Ramadan [a, b, *], Rabih Murr [a], Mahmoud Khaled [a, c], Abdul Ghani Olabi [d]

[a] Energy and Thermo-Fluid Group, School of Engineering, International University of Beirut, PO Box 146404, Beirut, Lebanon
[b] Associate member at FCLAB, CNRS, Univ. Bourgogne Franche-Comte, Belfort cedex, France
[c] Univ Paris Diderot, Sorbonne Paris Cité, Paris InterdisciplinaryEnergyResearch Institute (PIERI), Paris, France
[d] University of the West of Scotland, School of Engineering, High Street, Paisley, PA1 2BE, UK

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Energy
Heat recovery
Heat pump
Energy efficiency
Energy recovery
Energy management

ABSTRACT

To reduce the carbon dioxide foot print, it is unescapable to adopt an energy policy that incorporates simultaneously renewable energy systems as well as smart energy strategies such as heat recovery. In the frame of this view, a heat recovery approach is suggested. The heat is recovered from drain water. It is then utilized to enhance the performance of heat pump within two schemes. Directly by replacing the ambient air heating the evaporator and indirectly by preheating the air heated by the condenser. The suggested approach is a numerical and experimental method that, on one hand, relies on experiments to determine the temperature of the drain water and on the other hand, it uses an iterative procedure to solve the energy balance equation and the mass balance equation. To that end an in-house code is developed. It allows to evaluate the heat efficiency of the heat recovery system as well as the performance of the heat pump. It has been shown that using such system may enhance the Coefficient of Performance up to 400%. In addition, economic and environmental studies are performed to assess the economic and environmental impact of the proposed techniques.

1. Introduction

The fluctuation in the price of fuel as well as the red alert of the environmental situation require to take efficient steps in order to reduce the consequences of the energy crisis especially at the social and economic levels. Furthermore, the nature of the modern life style had led to a strong dependency on new technologies which in turn act like an energy sink. In other terms, our daily energy consumption is continuously increasing. That is why it becomes tremendously critical to find solutions that encounters the problem from its origin to its end. To put it another way, a robust energy strategy should include on one hand renewable energy [1–5] sources such as solar energy [6–11], wind energy [12–15], geothermal energy [16–19], tidal energy [20–23] and on the other hand it should reduce the energy consumption by adopting optimal strategy of control and management [24–27], as well as smart techniques to recover waste energy [28–30] and reuse it completely or partially in other applications.

Heat recovery concept has been applied to several applications such as internal combustion engine [31], Heating Ventilating and air conditioning systems, chimney, and other systems that dissipate waste heat [32–38] generally in form of hot air or exhaust gas. That said, many works have been dedicated to study the possibility of recovering heat from other hot fluid especially from hot drain water. From a thermal stand point, water was found to be more suitable for heat recovery than air or exhaust gas since it has higher heat capacity. In other terms, it allows to obtain better heat transfer. With this in mind, recovering heat from drain water could be performed by several techniques and for different purposes. Three different categories have been identified, direct drain heat recovery systems, indirect drain heat recovery systems and coupled heat recovery systems. In direct heat recovery systems, the heat of drain water was directly used to heat cold water such as residential supply water [39].

Many works have been dedicated to study the effect of the geometrical configuration on the heat recovery system. In Ref. [40] a horizontal drain water heat recovery system is studied. Manouchehri et al. [41] investigated the effect of the angle of inclination on the performance of heat recovery. Performance of vertical

* Corresponding author. Energy and Thermo-Fluid Group, School of Engineering, International University of Beirut, PO Box 146404, Beirut, Lebanon.
E-mail address: mohamad.ramadan@liu.edu.lb (M. Ramadan).

https://doi.org/10.1016/j.energy.2018.01.086
0360-5442/

geometry is also examined in different configuration [42–44]. Ramadan et al. [43] performed an experimental study on drain water heat recovery using helicoidal heat exchanger in vertical position. A parametric study was carried out to evaluate the performance as well as the effectiveness in terms of the cold-water temperature and the boiler outlet temperature. Other studies combined drain water heat recovery system to solar energy as in Refs. [45,46]. Furthermore, several works have been devoted to investigate the coupling between drain water heat recovery system and heat pump [45,47–52]. In other words, the concept of using the waste heat of drain to enhance the performance of heat pump or to provide a heat source for the evaporator. A review on wastewater source heat pumps was presented in Ref. [53]. The study examines the potential of heat recovery systems in recovering and reusing waste heat. Culha et al. [54] investigated types, construction methodology, classifications and utilizations of wastewater heat exchangers coupled with heat pump. Dong et al. [51] proposed heat pump water heater for shower assisted with recovery system from drain water. Baek et al. [55] suggested a compression heat pump system that utilizes recovered heat from sauna, and public baths. Kahraman et al. [56] tested experimentally the coupling of heat pump and drain water heat recovery under different conditions. Ni et al. [57], conducted a study on a grey water heat recovery system. The system is combined with a heat pump for space and water heating. The authors mention that such system allows an energy saving up to 57% compared to a conventional system. Chen et al. [58] designed a heat pump water heater coupled to shower wastewater. The authors present a thermodynamic model and develop a code using Matlab. Wallin et al. [59] underlined the performance of a vertical inline drain water heat recovery system combined with a heat pump. In Ref. [49] the authors revealed the effect of water flows in a heat pump - vertical drain water heat recovery system. Liu et al. [60] proposed an absorption heat pump and an electrical heat pump combined to a heat recovery system. Postrioti et al. [52] analyzed the performance of heat recovery from civil wastewater to supply heat pump heating system. The authors claim a 12% improvement of the COP with respect to air-water heat exchanger. The above-presented works show that heat recovery [35,38,43] is one of the most efficient techniques to reduce fuel consumption and CO_2 emissions. In the frame of this paper, a semi-experimental method for heat recovery from drain water is suggested. The recovered heat is used to enhance the performance of heat pump. Several scenarios are proposed and tested. The procedure consists in injecting experimental data into a numerical code in order to simulate the system. Moreover, economic and environmental studies are carried out to assess the economic and ecological dimensions of the suggested system.

This paper is organized as follows: Section 2 is devoted to introduce the concept of drain water heat recovery. Section 3 is dedicated to present the suggested heat recovery system. The computational code is presented in section 4. The experimental set-up is described in section 5. Results are discussed in section 6. The economic and environmental dimensions of the system are assessed respectively in section 7 and section 8 and finally the last section underlines the main concluding remarks of the paper.

2. Principle of drain water heat recovery

Drain water is a hot water that usually goes down the drain. It is a rich source of heat that is unfortunately not used. Indeed, the amount of heat contained in drain water depends on the characteristics of the application.

The principle of drain water heat recovery system (DWHRS) consists in recovering the heat rejected in drain water. Heat recovery applications should be defined depending on the range of temperature of the recovered drain water. The principle of heat recovery is described in Fig. 1. The drain water can heat or preheat a supply air by the usage of a heat exchanger. During winter periods, the drain water temperature is actually higher than the ambient air which may be below 10 °C in cold regions. In the frame of this paper, shower water is considered as the source of heat and heat pump as the recovery system. The main goal is to improve the performance of an air-to-air heat pump system.

3. Suggested DWHRS

Three different designs are suggested: condenser drain water heat recovery system (C-DWHRS), evaporator drain water heat recovery system (E-DWHRS) and mixed drain water heat recovery system (M-DWHRS).

In Fig. 2, the working fluid in the condenser is the supply and the working fluid in the evaporator is either the ambient air or the drain water depending on the DWHRS. In the other side, the refrigerant entering the compressor at state 1 (saturated vapor) is compressed to high pressure and temperature (state 2) before entering the condenser where it condenses at constant pressure to state 3 (saturated liquid) and releases heat to the working fluid that heats up. Then, the refrigerant flows through the expansion valve where an isenthalpic expansion takes place before flowing through the evaporator at state 4. In the evaporator, the refrigerant absorbs heat from the working fluid that cools down and evaporates at constant pressure to reach state 1. Besides, the "$\text{Pinch}_{\text{Evap}}$" is the minimum temperature difference between the working fluid and the refrigerant in the evaporator and the "$\text{Pinch}_{\text{Cond}}$" is the minimum temperature difference between the refrigerant and the working fluid in the condenser.

3.1. C-DWHRS

3.1.1. Principle of the C-DWHRS

In this system, drain water is only used to preheat the supply air by using a recovery heat exchanger (RHEX). The RHEX is a water-to-air heat exchanger where the het released by the hotter stream which is the drain water is absorbed by the colder stream which is the supply air. In order to reach the required temperature, this supply air passes then through the condenser of the air-to-air heat pump. The principle of this system is shown in Fig. 3.

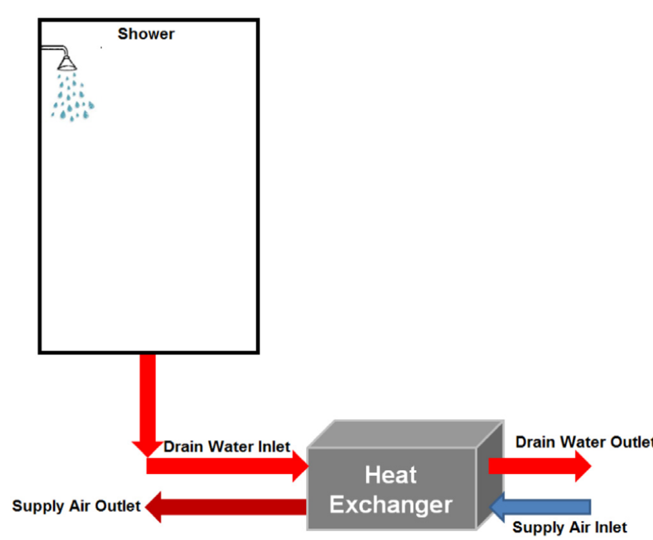

Fig. 1. Schematic of heat recovery principle inside a heat exchanger.

Please cite this article in press as: Ramadan M, et al., Mixed numerical - Experimental approach to enhance the heat pump performance by drain water heat recovery, Energy (2018), https://doi.org/10.1016/j.energy.2018.01.086