Experimental and Numerical Study for a Horizontal Wastewater Heat Recovery System

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Abstract: - This study aims to numerically and experimentally investigate the performance of a drain water heat recovery device. Consequently, a heat exchanger prototype was developed to integrate with classic rectangular shower trays of small dimensions. The proposed drain water heat recovery (DWHR) system was tested using a specially designed experimental stand. In addition, the experimental data were compared to numerical results based on Computational Fluid Dynamics (CFD) simulations. The values of effectiveness and Number of Transfer Units (NTU) achieved for the proposed DWHR system, based both on experimental and numerical data, are similar to those from the literature for analogous configurations of horizontal DWHR systems. Consequently, the heat exchanger prototype analyzed could represent a pertinent solution for heat recovery from drain shower water with minimum investment costs.

Key-Words: - Heat recovery, drain water, energy economy, experimental set-up, CFD modeling, heat exchanger effectiveness, heat exchanger Number of Transfer Units (NTU).

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1 Introduction

Energy saving is a fundamental concept of contemporary society, and it has been researched in an exhaustive manner in the last two decades. As a measure to reduce harmful gas emissions and create a suitable habitat, the researchers' attention has been directed towards identifying all possibilities for sustainable use of resources. In this context, it is worthwhile to mention that heating and domestic hot water (DHW) for buildings in the European Union (EU) represents approximately 75% of their total energy consumption, [1]. Consequently, there is a major interest in building energy efficiency. Concerning the DWH, it is known that the sewage system represents an important loss of energy, [2]. As a result, the research focussed on solutions for heat recovery from wastewater has developed more and more in the last 40 years, and drain water heat recovery (DWHR) systems are constantly improving, trying to reach their thermodynamic limits, [2]. DWHR units are normally based on heat exchanger devices, co-current flow, or counter flow [3], transferring heat between hot wastewater and cold fresh water. The two principal types of DWHR systems are vertical and horizontal systems, [2]. Vertical DWHR units can lead to adequate performance, with heat recovery efficiency of 20-75% depending on the heat exchanger configuration and working conditions (e.g. temperatures, water flow rates), [4], [5]. However, vertical DWHR units have limited applications as they demand more space, [6]. Consequently, horizontal DWHR systems have also been developed for configurations with reduced space. For instance, a horizontal DWHR system where the cold-water pipe is immersed in the larger wastewater pipe (Figure 1) has been analyzed, reaching an efficiency of over 50%, [7]. Furthermore, a financial analysis dealing with two solutions of horizontal DWHR systems has been carried out, [8]. The results showed that the configuration which leads to intensified turbulent flow for the wastewater allows major financial savings based on recovered energy. On the other hand, it has been shown, based on a short review of studies dealing with different types and applications of wastewater heat recovery systems, that about 50% of thermal energy could be recovered, [2].

In this context, a prototype for a horizontal crossflow heat exchanger to be integrated under shower trays was designed within CAMBI Research Center - Technical University of Civil Engineering of Bucharest. This heat exchanger prototype was integrated and tested using the experimental setup of the CAMBI Research Center, which is related to studies dealing with energy recovery applications from wastewater. It is worthwhile to mention that the experimental studies were performed both for unbalanced and balanced configurations (depending on the cold water flow rate in comparison with the wastewater flow rate), [9]. Moreover, Computational Fluid Dynamics (CFD) numerical models were developed for the proposed prototype of the DWHR system, and simulations were carried out for several configurations. Consequently, the heat transfer effectiveness and the number of transfer units (NTU) for the heat exchanger prototype were experimentally and numerically assessed.

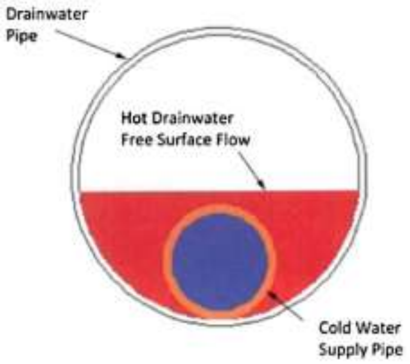

Fig. 1: Cross section of the proposed DWHR unit, [2]

2 Methodology

2.1 Drain Water Heat Recovery Systems

The operation of a wastewater heat recovery system is based on the use of hot water (37÷41°C) as a primary agent to heat cold water (the secondary agent) with a temperature of 10-15°C within a heat exchanger. Depending on the configuration, there are two main types of heat exchangers: parallel or countercurrent. It is considered that for a crossflow heat exchanger, theoretically, an efficiency of 100% can be achieved, while for parallel equipment the efficiency is limited to a maximum of 50%, [9].

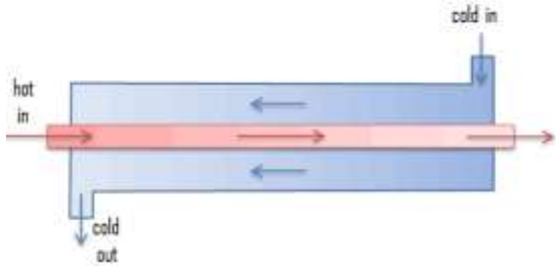

Fig. 2: Crossflow heat exchanger

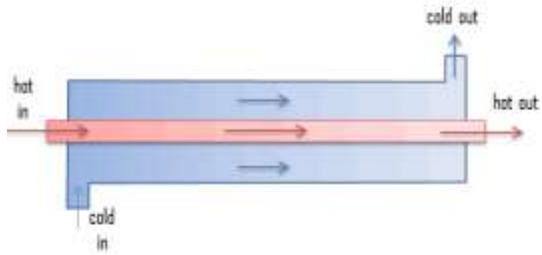

Fig. 3: Parallel heat exchanger

Figure 2 shows a crossflow heat exchanger while a parallel heat exchanger configuration is represented in Figure 3.

2.2 DWHR System Proposed

As the DWHR system was designed to be integrated under shower trays with reduced dimensions, the geometry of the equipment consists of a parallelepiped box measuring 610 x 460 x 78 mm (W x W x H) to which two tubes have been added, with a diameter of 40 mm and 32 mm respectively for the inlet/exit of grey water (Figure 4).

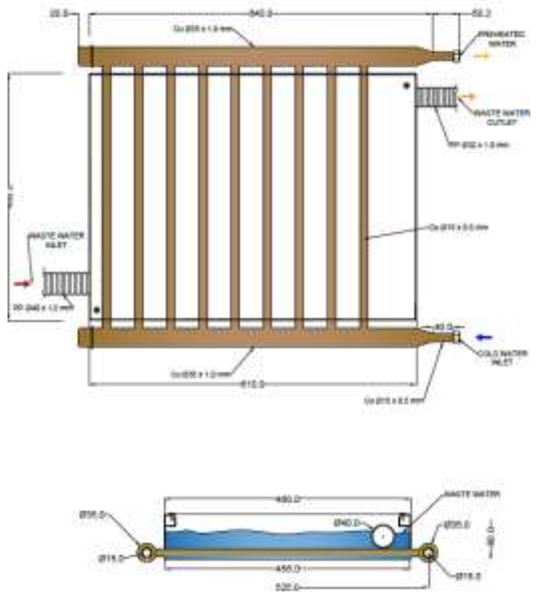

Fig. 4: Proposed DWHR system

Taking into account the intake and exhaust locations of the connections, the prototype can be considered a crossflow heat exchanger. Perpendicular to the length of the box, nine copper pipes were inserted (diameter of 15 mm and length of 475 mm), which were joined at the ends with two bigger pipes – distributor/collector (diameter of 35 mm and length of 710 mm). Finally, it should be also noted that analyses dealing with the optimization of lifecycle cost [10] were considered in designing the geometry and choosing the materials of the proposed DWHR system.

2.3 Experimental Setup

The integration of the heat exchanger prototype in the experimental set-up is presented in Figure 5 (the heat exchanger is placed under the shower tray).

Fig. 5: Experimental setup for the proposed DWHR system

A digital clamp-on ultrasonic flow meter (Siemens Sitrans FUP1010) with 1011 Universal sensors was used to measure the water flow rate through the two sides of the heat exchanger. In addition, 18 K-type thermocouples were used to determine the temperatures at different points of the DWHR system (Figure 6).

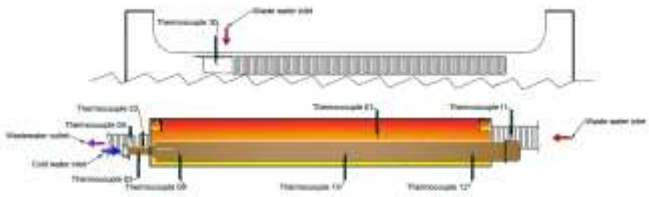

Fig. 6: Position of the thermocouples

Finally, the Almemo 5690-2 data acquisition system was used to record the values of temperatures.

2.4 Numerical Model

The CFD model was developed using the general-purpose, finite-volume, Navier-Stokes solver Ansys Fluent (version 15.0.0). The numerical model summing up is presented in Table 1.

It is worthwhile to mention that exhaustively grid-independent solutions analyses were carried out, based on several meshes. An overview of the final computational domain discretization taken into account (2,763,722 tetrahedral cells; 6,140,803 faces; and 785,796 nodes) is shown in Figure 7.

Table 1. Main features of the CFD model

Characteristic	Description
Fluid	Water
Flow	Three-dimensional, steady state, non-isothermal, turbulent
Computational domain discretization	Finite volumes, unstructured mesh (tetrahedral elements), 2,763,722 cells
Turbulence model	Shear Stress Transport (SST) turbulent kinetic energy-specific turbulent dissipation rate (k-ω), with low-Reynolds corrections
Boundary conditions	Inlets: water flow rate, temperature, turbulence parameters (turbulent intensity and hydraulic diameter) Outlets: outflow (continuative boundary, zero normal derivatives at the boundary for all quantities)
Numerical solution	Second-order upwind scheme; Velocity-pressure coupling: SIMPLE algorithm; Convergence acceleration: algebraic multigrid

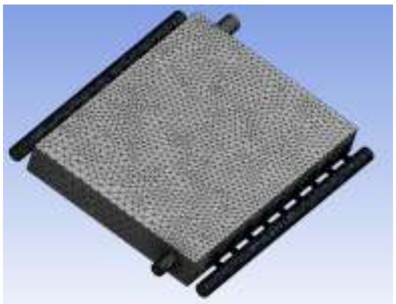

Fig. 7: Computational domain discretization

The justification for using the turbulence model k-ω SST - Shear Stress Transport [11] is based on the fact that this turbulence closure modeling was successfully validated against different industrial turbulent flow configurations, [12], [13]. Furthermore, the turbulence model k-ω SST represents a pertinent choice within our CFD model because a correct representation of both heat transfer in the boundary layers and turbulent flows in the regions far from solid boundaries is needed.

Steady-state simulations were carried out, therefore there were no particular problems regarding the stability of the numerical model. Nevertheless, convergence criteria were strictly monitored. The overall water flow balance within the heat exchanger for all the simulations was less than 0.0000002% during all iterations. In addition, temperatures in different points within the computational domain were observed during the simulations to assess the convergence of the computations. We present below the results for 4 points (Figure 8): α – at the middle of the heat exchanger box (at half of its height); β – in the heat exchanger box (at half of its height), near the preheated water collector; γ – in the heat exchanger box (at half of its height), close to the cold water distributor; δ – at the middle of the preheated water collector, in the center of collector pipe section.

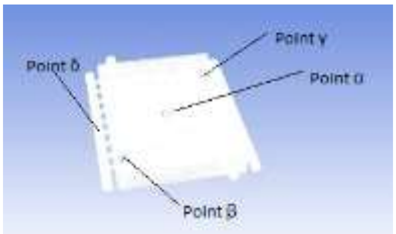

Fig. 8: Convergence checkpoints

The evolution and stabilization of temperatures in these points with the iterations for two wastewater temperatures (37 and 41°C) are presented in Figure 9 and Figure 10.

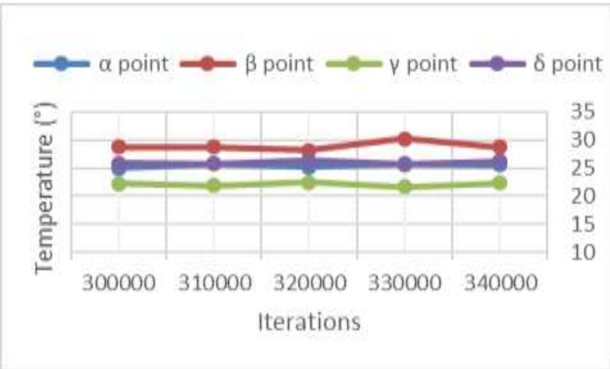

Fig. 9: Temperatures of points α,β,γ, and δ (inlet wastewater temperature: 37°C)

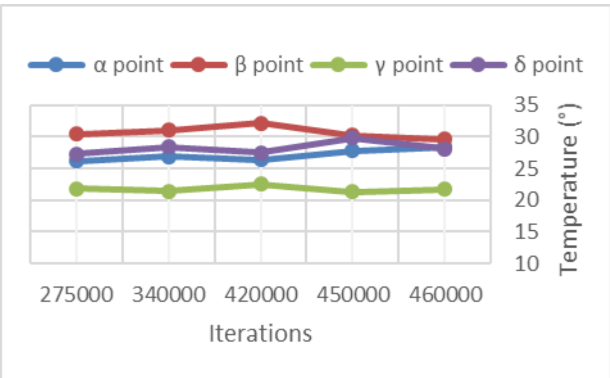

Fig. 10: Temperatures of points α,β,γ, and δ (inlet wastewater temperature: 41°C)

3 Results

We present below the results for the following study case: wastewater flow rate 5 l/min and cold water flow rate 4 l/min (unbalanced configuration). These flow rate values were taken into account for five different wastewater temperatures (37, 38, 39, 40, and 41°C) while the cold water temperature was constantly around 15°C according to measurements. The experimental and numerical results for these five situations are presented in Table 2.

Table 2. DWHR system: inlet/outlet temperatures

Inlet cold water: 15.60°C; Inlet wastewater: 37.00°C

Temperature	Experimental	Numerical
Outlet preheated water	18.10	20.87
Outlet wastewater	34.30	26.23

Inlet cold water: 15.40°C; Inlet wastewater: 38.00°C

Temperature	Experimental	Numerical
Outlet preheated water	18.60	21.26
Outlet wastewater	35.10	26.87

Inlet cold water: 15.40°C; Inlet wastewater: 39.00°C

Temperature	Experimental	Numerical
Outlet preheated water	18.90	21.55
Outlet wastewater	35.50	28.31

Inlet cold water: 15.40°C; Inlet wastewater: 40.00°C

Temperature	Experimental	Numerical
Outlet preheated water	19.30	22.00
Outlet wastewater	35.60	28.12

Inlet cold water: 15.40°C; Inlet wastewater: 41.00°C

Temperature	Experimental	Numerical
Outlet preheated water	19.60	22.27
Outlet wastewater	35.90	27.67

The data in Table 2 were employed to determine the thermal performance of the heat exchanger, in terms of effectiveness (ε) and Number of Transfer Units (NTU).

3.1 Heat Exchanger Effectiveness

One of the most widely used approaches to analyze the performance of heat exchangers is based on the comparison between their real and ideal behavior, known as "efficiency", [14]. This concept allows obtaining a clear image of a device's performance by assessing how close the analyzed system is to its best performance. Moreover, the values of heat exchanger effectiveness are extremely useful concerning further improvements of the investigated system. According to Eq. (1), the thermal effectiveness (ε) of a heat exchanger is as follows, [15]:

$$\varepsilon = \frac{(\dot{m}cp)_c \times (T_{c,out} - T_{c,in})}{(\dot{m}cp)_{min} \times (T_{h,in} - T_{c,in})} \quad (1)$$

where:

$\dot{m}$ - mass flow rate [kg/s];

$T_{c,out/in}$ - outlet/inlet cold water temperature [°C];

$T_{h,in}$ - inlet hot (drain) water temperature [°C];

c_p - specific heat capacity of water [KJ/kg°C]; subscript c refers to the cold water side while subscript min refers to the lesser of cold/hot side quantity.

As a result, based on the Eq. (1), the DWHR system effectiveness variation on different wastewater temperatures is shown in Figure 11.

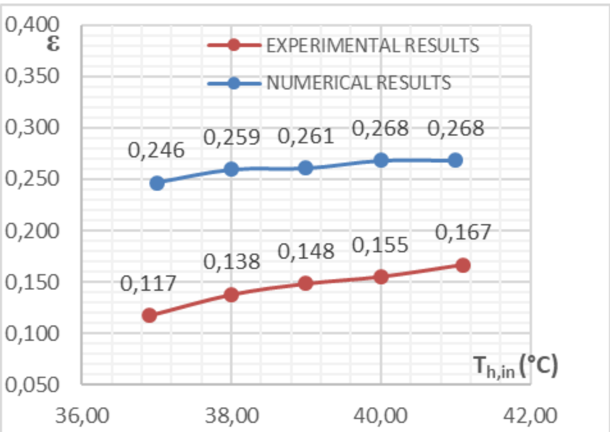

Fig. 11: DWHR system effectiveness

It can be observed that the DWHR unit effectiveness increases slightly with wastewater temperature. Furthermore, the values of effectiveness reached by the proposed prototype are comparable to those from the literature for similar configurations of horizontal DWHR systems, [9].

3.2 Heat Exchanger Number of Transfer Units

Another dimensionless parameter typically used to assess the performance of heat exchangers is the Number of Transfer Units (NTU). This parameter is useful to optimize the geometric and design of heat exchangers, considering overall heat transfer coefficients, transfer area, fluid flow rate, and heat capacity. NTU can be determined as follows, [16]:

$$NTU = \frac{\varepsilon}{1-\varepsilon} \quad (2)$$

NTU values obtained based on both experimental and numerical results are shown in Figure 12.

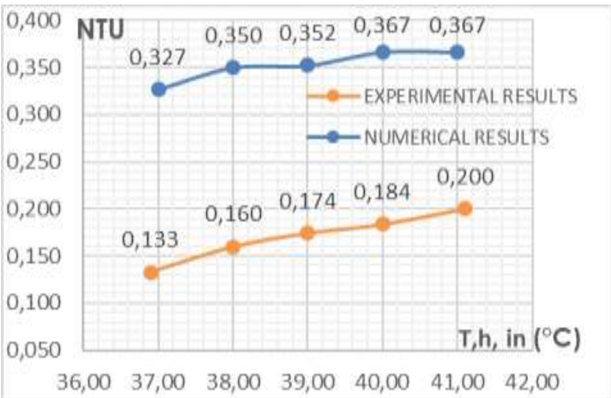

Fig. 12: DWHR system NTU (Number of Transfer Units)

The data from Figure 9 indicate the same trend (experimentally and numerically): the greater the gray water temperature, the higher values of NTU can be obtained.

4 Conclusions

The main objective of this study was to investigate the thermal behavior of a DWHR prototype to be incorporated under classic shower trays with reduced dimensions. The values achieved for effectiveness are experimentally around 12-17% and numerically between 25-27% while those for NTU are 13-20% (experimentally) and 32-37% (numerically). These results show that the performance achieved for the proposed DWHR system is satisfactory, considering the prerequisites imposed for the prototype: limited space available under the shower tray, low-cost construction, and simple maintenance. On the other hand, these results indicate that the CFD model should be improved as there are discrepancies compared to experimental data. Excluding the uncertainty of the experimental data (which also contributes to these experimental-numerical differences), the numerical model must be improved regarding the prediction of the heat transfer at the level of the heat exchanger tubes. The validation of the numerical model will allow us to extrapolate the simulations for other (improved) configurations of the DWHR unit investigated here. For instance, further focus will be on solutions concerning increased heat transfer surface without affecting the overall sizes of the DWHR system (e.g. introducing fins on the pipes of the heat exchanger) or on improving flow turbulence by adding special elements within the heat exchanger.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Dragoș Purghel carried out the experimental study and developed the numerical model, writing - original draft.
- Cătălin Teodosiu was responsible for conceptualization, methodology, supervision, investigation of results, visualisation, writing – review & editing.

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Conflict of Interest

The authors have no conflicts of interest to declare.