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An investigation of drain-side wetting on the performance of falling film drain water heat recovery systems

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ABSTRACT

Falling film drain water heat recovery (DWHR) systems are single pass, vented heat exchangers. The heat from the drain water is transferred through the DWHR system to the incoming cold mains water, recovering otherwise wasted energy. This article discusses the theory behind DWHR systems, and examines how drain-side wetting affects performance. It also describes the apparatus built by the Solar Thermal Research Laboratory (STRL), at the University of Waterloo, for testing the effectiveness of DWHR systems.

The results show that as the flow rate increases, the effectiveness of the DWHR pipe decreases. The data also indicates that there is a Critical Flow Rate (CFR) below which the performance of a DWHR pipe cannot be extrapolated. The inability to extrapolate is due to the incoming drain water not repeatedly wetting the same amount of area on the pipe's interior wall. This CFR is dependent on the diameter and interior surface characteristics of the pipe.

1. Introduction

As global energy consumption continues to rise, energy conservation is often recognized as an excellent alternative to the development of new energy sources. Energy conservation is generally regarded as reducing usage, but can also include the reclamation of energy. An example of energy that can easily be reclaimed is the energy stored in warm drain water.

Surveys have shown that in the year 2010, 16.4% of the total energy consumed in residences in the U.S. is for water heating. That represented approximately 2025 PJ, which equates to approximately 17.7 GJ of energy consumed annually per household [1]. It is also estimated that Americans spent $33.8 billion on residential water heating in that year alone [2]. This highlights the fact that the energy consumption associated with water heating is immense and there is significant potential to reclaim heat from drain water.

One device that is suitable for reclaiming drain water energy in new construction and retrofit applications is the falling film drain water heat recovery system (DWHR) (Fig. 1). In general, a DWHR system is a single pass, double walled, counter flow, vented falling film heat exchanger. It is comprised of a large diameter copper pipe, typically between 5.1 to 10.2 cm (2 to 4 in.), set to match the size of the drain stack it replaces. Wrapped tightly around the large pipe is a coil of small diameter copper piping through which the cold mains water is passed. The warm drain water flows into the top of the large diameter copper pipe, "wetting" the inside by filming itself to the inner wall and exiting at the base after transferring thermal energy to the copper. Cold mains water flows into the small diameter pipe at the bottom of the heat exchanger and extracts heat from the large pipe until it exits at the top of the DWHR unit warmed.

DWHR systems are becoming more common in new and energy efficient construction. In response to this, code and incentive programs are working to develop rating procedures for these systems. In Canada, for example, the "National Energy Code of Canada for Buildings 2011" was updated in 2012 to incorporate DWHR systems [3]. To standardize test methods and results for DWHR pipes, the Canadian Standards Association (CSA) recently produced Standard B55.1-12 *"Test method for measuring efficiency and pressure loss of drain water heat recovery units"* [4]. The standard includes the requirements for the design and configuration of a testing apparatus which simulates the performance of a DWHR system in a typical installation. Unfortunately, these rating procedures were being developed in the absence of any analysis of how the systems perform in reality.

The objective of the current work is to examine the effect of drain-side wetting on the equal flow performance characteristics

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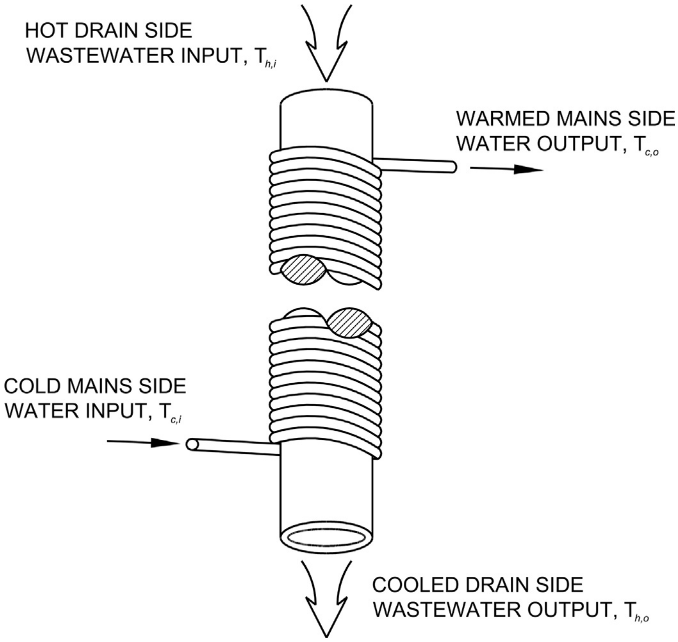

Fig. 1. Diagram of a DWHR system.

of DWHR systems. To do this, an apparatus was constructed at the University of Waterloo's Solar Thermal Research Laboratory (STRL).

2. Theory

Heat exchangers are most often rated using the effectiveness-*NTU* or ε-*NTU* method [5]. By this method, the effectiveness, ε, at which a DWHR system extracts energy from the drain water can be expressed as the ratio of heat transfer, q, to the maximum heat transfer, $q_{\max}$, which can occur in the heat exchanger:

$$\varepsilon = \frac{q}{q_{\max}} \tag{1}$$

The heat transfer occurring in the DWHR system can be evaluated using the drain-side or mains-side flows, using:

$$q = \left(\dot{m}C_p\right)_h \left(T_{h,i} - T_{h,o}\right) = \left(\dot{m}C_p\right)_c \left(T_{c,o} - T_{c,i}\right) \tag{2}$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat of the water, and T is the fluid temperature. Referring to Fig. 1, the subscripts h and c represent the hot drain-side and cold mains-side flows, respectively. The subscripts i and o refer to the inlet and outlet, respectively.

The maximum heat transfer in the DWHR system can be evaluated by combining the maximum temperature difference in the heat exchanger, with the minimum fluid heat capacity.

$$q_{\max} = \left(\dot{m}C_p\right)_{\min} \left(T_{h,i} - T_{c,i}\right) \tag{3}$$

where the subscript min refers to the lesser of $\left(\dot{m}C_p\right)_h$ and $\left(\dot{m}C_p\right)_c$ This yields:

$$\varepsilon = \frac{\left(\dot{m}C_p\right)_c \left(T_{c,o} - T_{c,i}\right)}{\left(\dot{m}C_p\right)_{\min} \left(T_{h,i} - T_{c,i}\right)} = \frac{\left(\dot{m}C_p\right)_h \left(T_{h,i} - T_{h,o}\right)}{\left(\dot{m}C_p\right)_{\min} \left(T_{h,i} - T_{c,i}\right)} \tag{4}$$

The DWHR system operates when hot water is dumped through the drain-side at the same time as cold water is drawn though the mains-side. As a result, the majority of the energy collected is under equal flow conditions. By assuming that C_p does not change significantly across the DWHR system, it can be said that:

$$\left(\dot{m}C_p\right)_h = \left(\dot{m}C_p\right)_c = \left(\dot{m}C_p\right)_{\min} = \dot{m}C_p \tag{5}$$

The DWHR system's effectiveness can therefore be determined using:

$$\varepsilon = \frac{\left(T_{c,o} - T_{c,i}\right)}{\left(T_{h,i} - T_{c,i}\right)} = \frac{\left(T_{h,i} - T_{h,o}\right)}{\left(T_{h,i} - T_{c,i}\right)} \tag{6}$$

thereby reducing the complexity of determining a given pipe's effectiveness to a simple ratio of the inlet and outlet fluid temperatures.

A DWHR system can also be classed as a concentric tube heat exchanger. Given this, and the relationship shown in Eq. (5), it can be shown that the effectiveness of a DWHR system could be expressed as [5]

$$\varepsilon = \frac{NTU}{(1 + NTU)} \tag{7}$$

NTU represents the number of transfer units and is defined as:

$$NTU = \frac{UA}{\left(\dot{m}C_p\right)} \tag{8}$$

where A represents the heat transfer area, and U the overall heat transfer coefficient [5]. Combining, Eq. (7) becomes:

$$\varepsilon = \frac{UA/\left(\dot{m}C_p\right)}{1 + UA/\left(\dot{m}C_p\right)} = \frac{UA}{\left(\dot{m}C_p\right) + UA} \tag{9}$$

In fundamental texts, the *NTU*s for a given heat exchanger is assumed to be constant. This, however, is often not the case. In reality, the *UA* product for DWHR systems has been seen to vary significantly with flow rate [6], or more specifically, the wetted area of the drain-side film. At high drain-side flow rates the entire interior surface of the drain-pipe will be covered by a falling film, while at low flow rates, the flow may delaminate. When the area covered by the falling film of water is less than the overall inner surface area of the pipe it is referred to as *partial wetting*. *Full wetting* occurs when the entire inner surface area of the pipe is covered by a film of falling hot water. It is further noted that even when fully wetted, the falling film may not be uniformly distributed. The *UA* product will vary significantly with wetting, and this should be apparent in the characteristic performance curve for the DWHR system.

The theoretical characteristic behaviour is shown in Fig. 2. At high flow rates, the quantity of water is enough to cover the entire inner surface of the pipe keeping the wetted area constant. This range of high flow rates is referred to as the *stable full wetting* region. Conversely, very low flow rates only allow a small trickle of water to stream down the pipe. Since the flow rate is so low, the area covered by the steam of water remains constant. This range of low flow rates is referred to as the *stable partial wetting* region. Between these two regions of *stable full wetting* and *stable partial wetting* there will be a *transition region*. In this region the flow rate of water is not high enough to cover the entire surface area of the pipe, nor is the flow low enough to be limited to a single stream of water traversing down the pipe. The wetted area would differ from test to test, even at the same flow rate, depending on the path the water takes. Then, within the transition region, tests would generate a range of different effectiveness values, depending on the area covered in water.

A transition region between *stable partial wetting* and *stable full wetting* implies hysteresis. Conditions occurring shortly before a test reaches a steady wetted area might have a direct bearing on the test. For example, an area covered by water at the current flow rate could depend on the area that was covered with water shortly before. Presumably, due to the hydrophobic nature of copper, the wetted area would be greater if the test was begun at a high flow rate and then reduced to a desired flow rate. Conversely, if the test was started at a very low flow rate and then increased to the same desired flow rate the wetted area would be smaller.