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Impact of small tilt angles 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 heat exchangers used to recover heat from the building graywater, mainly from showers, to preheat the incoming mains water. These systems are designed to be installed vertically, as is required for the formation of a uniform falling film. A perfectly vertical installation, however, is not always obtainable, and several building designers and DWHR manufacturers have shown an interest in estimating the reduction in DWHR performance for non-vertical installations.

The current work aims to address this issue by measuring the change in DWHR effectiveness for tilt angles up to 15° off vertical, and by producing generalized guidelines regarding how a system performs in a non-vertical orientation. In general, it has been shown that the performance of DWHR decreases as the installation angle with respect to the vertical increases. The results show that for an installation angle of 2°, a maximum performance drop of 4% relative to a vertical installation could occur. For installation angles larger than 2°, the performance drop becomes large and variable for all pipe diameters. Visible observations show that non-uniform film formation is the cause of this.

1. Introduction

Drain water heat recovery (DWHR) systems are heat exchangers which transfer heat from warm outgoing graywater to cold incoming potable water. A DWHR system is most often a falling film counterflow heat exchanger consisting of small diameter copper pipes wrapped around a larger diameter copper drain pipe, as shown in Fig. 1 [1]. Heat transfer is from the warm drain-side water to the cold mains-side water, which recovers some of the otherwise wasted energy. The potential for energy and cost savings has led to the development of a variety of DWHR designs, which all share this general configuration.

DWHR systems have potential to be an important aspect of building energy conservation. A study conducted in Great Britain in the 1970s determined that a household graywater heat recovery system could save 10% of total household energy consumption, recovering the capital cost in only three years [2]. More recently, studies conducted at the Manitoba Advanced House in Winnipeg, Canada estimated that 50% of a typical family's annual domestic hot water load could be recovered [3]. This figure is corroborated by a U.S. Department of Energy study which concluded that 30–50% of domestic hot water energy can be saved using a DWHR system [4].

The performance of DWHR systems relies on water falling as an annular film and wetting the inner surface of the drain pipe. This phenomenon results in high heat transfer rates on the drain-side of the system. Heat transfer surface area is maximized and the water film thickness which resists conduction is minimized. DWHR systems are designed to be installed vertically, which allows water to fall as a relatively uniform thin film [5–7].

There are few research papers that measure the performance of DWHR systems experimentally. Collins et al. [8] investigated the effectiveness of three different DWHR systems and developed the characteristic effectiveness curves for their performance as a function of flow rate. Schuitema et al. [9] analyzed the performance of a DWHR system installed in a high performance residential dwelling in the Netherlands. The study showed that the DWHR system reduced domestic hot water energy usage by up to 29.6%. A study by Zaloum et al. [10] focused on measuring the fuel savings associated with three designs of DWHR systems by installing them in a residential dwelling in Canada. The results showed that DWHR systems reduced gas consumption by 9 to 27%. None of these studies have investigated the performance of DWHR systems at tilt angles off vertical.

In new construction, proper care can enable accurate vertical installation of DWHR systems. However, an accurate vertical

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Nomenclature

ε	effectiveness of the DWHR pipe (dimensionless)
ε_r	effectiveness ratio, effectiveness at a given angle divided by effectiveness at vertical (dimensionless)
$T_{c,i}$	temperature of mains-side, cold-water, inlet (°C)
$T_{c,o}$	temperature of mains-side, cold-water, outlet (°C)
$T_{h,i}$	temperature of drain-side, hot-water, inlet (°C)
$T_{h,o}$	temperature of drain-side, hot-water, outlet (°C)
θ_T	tilt angle with respect to the vertical (°)

installation may not be possible in many retrofit applications. Several building designers and DWHR system manufacturers have shown interest in estimating the reduction of DWHR performance for non-vertical installations. The motivation of the current work is to address this need. Straying from a perfectly vertical orientation will likely cause the film to be non-uniform around the drain pipe's inner circumference, reducing the performance of the heat exchanger. The purpose of this study is to identify how sensitive DWHR systems are to tilt angles away from vertical, and to provide insight on what installation angles are acceptable.

2. Method

An apparatus capable of testing the performance of DWHR systems has been built at the University of Waterloo, Waterloo, Canada. The test platform conditions separate cold and hot volumes of water to prescribed set point temperatures. Approximately 180 L of cold water can be conditioned to between 5 and 20 °C, and approximately 360 L of warm water can be conditioned to between 30 and 60 °C. The system is capable of conditioning water to desired temperatures within these ranges to an accuracy of ±0.5 °C.

Once conditioned, a vane pump and bypass combination allows the water to be driven through the system at flow rates ranging from 1 to 26 liters per minute (LPM). Water is first taken from the cold water reservoir and pumped through the cold mains-side of the DWHR system. The water sent to the warm temperature reservoir pushes an equal volume of warm water to the drain-side of the DWHR system. The design is such to inhibit mixing of incoming and outgoing water at this point. Water exiting the DWHR system is sent to a temporary storage tank to wait for the next conditioning cycle.

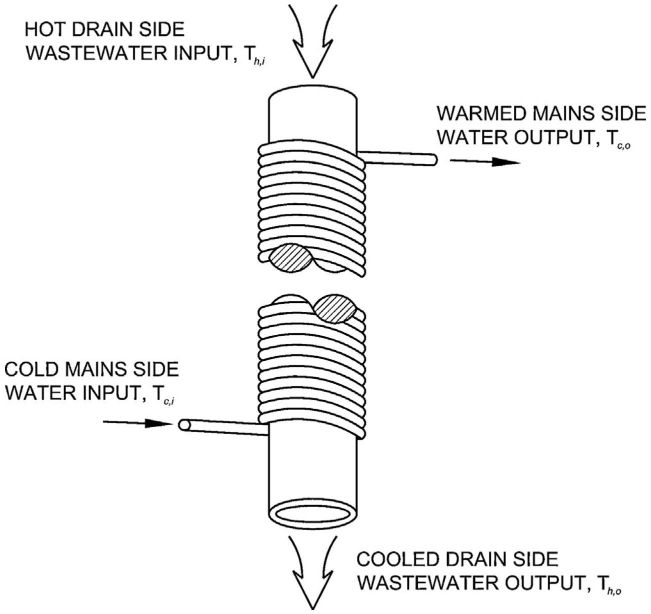

Fig. 1. Construction and flow paths of a generic DWHR system [1].

Table 1
Diameters and lengths of DWHR systems studied.

Pipe No.	Diameter (cm)	Length (cm)
1	5.1	122
2	7.6	92
3	7.6	122
4	7.6	153
5	10.2	122
6	10.2	153

Water temperatures and the flow rate in the system are measured using ISO 17025 calibrated resistance temperature devices (RTDs) and a turbine flow meter. The RTDs have an accuracy of ±0.1 °C and the flow meter has an accuracy of ±1% of reading [11,12]. Steady state is achieved through stabilization of the inlet and outlet temperatures to less than 0.2 °C variation and the flow rate to less than 0.2 LPM variation. A detailed description of the test platform and its components are available in a previous publication by Beentjes et al. [1].

DWHR systems are typically rated by their thermal effectiveness obtained under equal flow conditions, and at specified temperature differences and flow rates. For example, CSA standard B55.1-12 requires that tests be performed at flow rates of 5.5, 7, 9, 10, 12, and 14 LPM with a cold supply-side temperature ranging from 7 to 17 °C and a temperature difference between cold and hot sides within 27 and 29 °C. Because of the equal flow requirement, and assuming constant fluid density and specific heat, the effectiveness can be calculated based only on temperature differences across the DWHR system [8,13]:

$$\varepsilon = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \tag{1}$$

The effectiveness of DWHR systems can be measured with an uncertainty of ±0.6% full scale using the test apparatus [1].

In the North American market, DWHR systems are available in various lengths with typical nominal drain diameters of 5.1, 7.6 and 10.2 cm (2, 3 or 4 in.). For this study, six DWHR systems of various lengths and diameters were chosen as listed in Table 1.

The thermal effectiveness of each DWHR system was measured at flow rates of 5.5, 9.5, and 14 LPM, and at tilt angles from vertical of 0°, 2°, 5°, 10°, and 15°. The cold and hot-side temperatures of 10 ± 0.5 °C and 38 ± 0.5 °C were maintained for the mains-side inlet and drain-side inlet respectively. To achieve the maximum wetting area in the pipes, each test is started with a high flow rate of 20 LPM and gradually lowered to achieve the desired flow rate. The drain-side flow was photographed to observe the behavior of the falling film.

The CSA test standard requires DWHR systems to be installed at no more than 2° from vertical orientation during testing [13]. The test platform meets this angular requirement, but also allows testing of DWHR systems at angles further from vertical. The performance at tilt angles away from vertical is assessed to evaluate variations to be expected in standardized tests and service installations, both of which can never be perfectly vertical.

The tilt angle measurement was performed using a plumb-bob and linear measurement, with trigonometry used to calculate the angle. The experimental setup and measurement method are depicted Fig. 2. This method results in significantly less error than using an inclinometer, which would have an uncertainty of at least ±0.5° due to least count on a protractor scale. Given the distance