EVALUATION OF A SYSTEM FOR RECOVERY OF WASTE HOT WATER HEAT ENERGY

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Title: System for Recovery of Waste Hot Water Heat Energy
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SUMMARY

The inventor has been granted a patent for a falling-film counterflow heat exchanger to be used to transfer the thermal energy contained in waste water, which is discharged from domestic, commercial, and industrial sources, to potable or process water. The heat exchanger must be oriented vertically so as to establish the falling film within its central pipe which also serves as part of the discharge or sewer line. Hydrostatic pressure, provided by the utility or process, is used to force water axially around the outside of the central pipe and, thereby, extract some of the thermal energy contained in the falling film of waste water. Falling film heat transfer is excellent. The heat exchanger is simple in design and is completely passive.

The inventor's heat exchanger is only self-cleaning in applications where detergents are occasionally present in the waste water. In most commercial and industrial applications this is not true. For these applications, the imported POZZI RCR heat recuperation liquid-to-liquid heat exchanger has a proven service life and is recommended where self-cleaning is required. The POZZI device is not recommended for potable water applications, however, its orientation is not restricted as is the inventor's heat exchanger.

A model of the falling-film heat exchanger has been installed in the inventor's home since early 1980. By measuring temperatures then and now, he has demonstrated that the heat exchanger has not degraded. However, this heat exchanger design and a subsequent larger model are not considered fail-safe and, therefore, cannot be used for potable water service. The design has been modified to correct this problem, and it is this design that is evaluated herein.

The redesigned heat exchanger has been evaluated for the domestic market. Residences in the U.S. annually consume 2.23×10^{15} Btu or 2.23 Quads to heat water. Of this amount, 1.37 Quads are delivered at the tap, and 0.96 Quad shows up in the waste water. Since the inventor's heat exchanger only functions when the potable and drain waters flow simultaneously, and since only about 50% of the households have basements which are needed for vertical installation of the heat exchanger, then only 0.31 Quad of energy in the waste water is a candidate for recovery. Of this energy, the redesigned heat exchanger can recover about 0.16 Quad. This is a significant amount of energy. If all U.S. domestic water heating was to be accomplished by burning oil, then the annual oil consumption would be reduced by about 2 billion gallons if this device is installed in all houses with basements.

For homes which have electric hot-water heaters, the simple payback of this heat exchanger is about 2 years; for homes with oil heating it is about 4 years; and, for homes with natural gas heating it is about 6.4 years. The paybacks for the inventor's heat exchanger are three times more rapid than those for solar hot-water systems even with their 40% Federal tax credits.

As the M.I.T. Solar House experiments demonstrated, domestic hot-water-heating demand is quite variable from month-to-month and year-to-year. Some of these variations are clearly the result of annual changes in supply water temperature but the remainder must be caused by variations in human habits. While the inventor's heat exchanger is very responsive thermally because of its small heat capacity, it is not known how variations in human habits will affect its heat recovery performance. Clearly, this is an area which requires further investigation.

1. Background

The inventor has conceived a counterflow liquid-to-liquid heat exchanger which consists of a large central pipe surrounded by a second PVC pipe so as to form an annular space therebetween. The heat exchanger is oriented so that the axis of the central pipe is vertical. If the quantity of liquid flow in the central pipe is small, it will flow down its internal circumference in a thin film under the influence of gravity. A second liquid is forced to flow upwards in the annular space and, thereby, counterflow of the two liquids is achieved.

On April 28, 1980, the inventor installed a 3-foot long model of the above described heat exchanger in the sewage line in his home. The incoming water-supply pipe was connected to the bottom inlet leading to the annular space, and the outlet was connected to both the makeup line supplying the hot-water heater and to the cold-water line supplying the house. Under this arrangement, the mass-flow rate of potable water in the annulus is equal to the mass-flow rate of waste water when, for example, a person is taking a shower.

In 1980, the inventor measured the decrease in temperature of the waste water and the temperature increase of the potable water across the heat exchanger when the shower was operating. The calculated effectiveness of the heat exchanger was between 27 and 36% -- That is, between 27 and 36% of the thermal energy in the waste water was transferred to the potable water. Recent measurements under identical circumstances confirm that the effectiveness of the heat exchanger has not changed during the intervening years.

On July 14, 1980, the inventor filed for a patent on the above described concept, however, the patent was so poorly written that it had to be abandoned in view of cited prior art. The inventor has filed for a new patent which has very recently been granted.

In 1982, the inventor made a new model of his heat exchanger. This model was 5-foot long, and into the annulus he inserted a layer of ordinary aluminum window screen in order to promote turbulence. Brookhaven National Laboratory tested this new model under unbalanced mass-flow rate conditions and reported heat exchanger effectivenesses varying between 80% and 90% (Reference 10). The inventor complained that, since the tests were not conducted under balanced flow conditions, the test results were not of any use to him in advancing his case.

OERI has twice rejected the subject heat exchanger. On May 2, 1984, the rejection was based generally on the preception, abetted by the inventor's incomplete disclosure, that his heat exchanger was like the many others which have not achieved commercial success in this very difficult application. The inventor appealed for reconsideration and was again rejected on December 24, 1985. On this occasion, OERI argued that the economics of the proposed heat exchanger were unattractive and that its design was not technically acceptable for potable-water use. Subsequently, the inventor personally presented his case but the presentation was badly fragmented and he did not endeavor to satisfy OERI's technical objections.

2. Falling Films

Falling-film evaporators and exchangers are widely used in industry (Reference 3) because excellent heat and mass transfer can be obtained without the need for excessive pumping power. As a result of the work done by Friedman and Miller (Reference 9) and others, the behavior of falling films inside tubes is well understood. McAdams (Reference 2) and others (Reference 3) have documented the heat transfer behavior of falling films.

The inventor has been very fortunate to select falling-film technology in the design of his waste-water heat exchanger, especially for domestic use. This is because the pipe for drainage is sized for toilet use and is, therefore, much larger than is required for the normal drainage during which time the device is expected to operate in a heat transfer mode; and, because the use of detergents combined with high film velocities scrubs clean the inside surface of the central copper pipe of the heat exchanger -- this ensures good wetting and heat transfer.

The film thickness and velocity were calculated for the inventor's 3-inch ID drainpipe which comprises the central pipe of his heat exchanger. At a waste-water massflow rate of 0.444 gallons per minute (gpm), the film thickness is 11.5 mils if uniform, and the velocity is 1.32 ft/second; and, at a mass-flow rate of 3.11 gpm, the film thickness is 27.2 mils and the velocity is 3.88 ft/second. The lower flow is laminar and the higher flow is turbulent, however, because the Froude number exceeds one in all cases, the film surface motion is always wavy. The Fourier thermal transfer number is a function of the length of the heat exchanger. At the transition Reynolds number of 2000 (1.33

gpm), the thermal completion efficiency varies from 44% for a 1/2-foot long heat exchanger to 91% for a 3-foot long heat exchanger. Wavy motion in the film will increase the completion efficiency for short-length heat exchangers, however, in the laminar flow region, McAdams found that the heat transfer benefit is not great; therefore, short-length heat exchangers of this type should be avioded. This precludes the under-the-sink applications which the inventor spent so much time investigating.

3. Thermal Analyses

The inventor was contacted in order to obtain the details of construction of his home and Brookhaven test units. This information was used to analyze the thermal performances of these units.

First, some definitions are required in order to aviod perpetuating the confusion which has surrounded the inventor's endeavor. When the heat-capacity rate (the mass-flow rate multiplied by the specific heat of the fluid) of waste water equals the heat-capacity rate of the potable water, the heat exchanger is said to be balanced. This is the condition preferred by the inventor and the heat exchanger installed in his home is operating under balanced conditions. For the under-the-shower and under-the-sink applications, the heat exchanger is unbalanced; that is, the heat-capacity rate of the waste water is greater than the heat-capacity rate of the supply water. Brookhaven only tested the heat exchanger under unbalanced flow conditions and the inventor has been unable to transform this data to his preferred balanced flow conditions.

The thermal performance of a heat exchanger is measured by its effectiveness. For a balanced heat exchanger, the effectiveness is defined by the ratio of the heat recovered divided by the total heat capable of being recovered. The specific heats of the cold and waste waters can be assumed to be equal, and the total heat capable of being recovered is the product $\omega C_p (T_w - T_c)$, where ω is the mass-flow rate of waste water (equal to the mass-flow rate of cold water), C_p is the specific heat of water, T_w is the incoming waste water temperature, and T_c is the incoming cold water temperature. If the cold water temperature increase is given by ΔT_c, then the effectiveness is given by the ratio $\Delta T_c / (T_w - T_c)$ since ω and C_p are the same for both the waste water and the cold water.

The same definition for effectiveness applies for an unbalanced heat exchanger, however, in this case the total heat capable of being recovered is restricted by the ability of the liquid stream having the lower heat-capacity rate to accept thermal energy without violating the second law of thermodynamics. Since in all applications considered herein, the heat-capacity rate of the cold water is either less than or equal to that of the waste water, the effectiveness is always defined by $\Delta T_c / (T_w - T_c)$ as in the balanced case above. It is axiomatic that at any given value of cold water heat-capacity rate, the effectiveness of the heat exchanger will increase as it becomes more unbalanced.

The heat exchanger which is installed in the inventor's home was analyzed (References 1,2,3). At a balanced mass-flow rate of 2 gpm, the effectiveness is calculated to be 27.1% and its conductance is 372.9 Btu/hr-^{o}F. The major resistance to heat transfer (74.9% of the total) occurs in the annular cold water film. The resistance in the falling film is 24.7% of the total and the copper central pipe wall resistance is insignificant. No allowance was made for waste-side fouling, and it does not appear that any is required if copper is employed for the drain pipe. The inventor has reported the effectiveness of this heat exchanger to be between 27 and 36% -- the mass-flow rate was not measured and if the mass-flow rate is less than 2 gpm, the above calculated effectiveness is then increased (30% is the effectiveness at a mass-flow rate of 1 gpm).

The inventor thought that the flow in the annulus was laminar in his home model. At a mass-flow rate of 2 gpm, the Reynolds number is close to transition (2000). He proceeded to construct a 5-foot long second model which, herein, is referred to as the Brookhaven model. Into the annular space between the central copper pipe and the PVC outer pipe, he inserted a layer of aluminum window screen. Because the PVC tube ID was not uniform and the annular gap was only 3/64 of an inch, difficulty was experienced in assembly.

The Brookhaven heat exchanger was also analyzed by the same methods as those employed above. For Brookhaven's Test No. 3 conditions, the heat exchanger cold-to-hot flow heat-capacity ratio was 0.425 and the measured effectiveness was 80%. Unfortunately, the cold mass-flow rate was only 0.92 gpm which created conditions of ambiguous heat transfer in the annular film; even with the aluminum screen present. If turbulent flow is assumed to occur in the annulus, the calculated effectiveness is 70%. In this case, 23% of the resistance is in the falling film and 77% is in the annular film. The overall conductance is 683 Btu/hr-^{o}F. Insertion of the screen increased the overall conductance by 10% over that which would have been obtained without the screen, and indications from the Brookhaven test results are that its benefit may be somewhat greater.

The inventor measured the effectiveness of the Brookhaven model under balanced flow conditions at a mass-flow rate of 2.4 gpm. He obtained an effectiveness of 45% and the calculated effectiveness is 46%. Under these flow conditions, the overall conductance is 1033 Btu/hr-^{o}F. The resistance of the falling film in this case is 38.6% of the total and the annular film resistance is 61.4% of the total -- this is a much better balance since the annular flow is clearly turbulent at the higher mass-flow rate and the analysis is, consequently, more accurate.

4. Problems with the Brookhaven Model Design

Aside from the incompatibility of aluminum and copper, inserting a screen in the annular space creates a filter which, in time, will become blocked from trapped sediment. The screen does improve heat transfer especially in the laminar flow region. The screen also serves to space the rather uneven PVC pipe away from the central copper pipe and, thereby, creates a more unifrom annulus. On balance, however, a filter is not what is desired in this application.

For the reasons given by Skartvedt in Reference 8, a fail-safe design is considered a mandatory requirement for potable water applications such as the present one. OERI informed the inventor of this requirement. Ignoring this requirement places the inventor and the company selling this product in a position of negligence in any legal action which may arise from its use or misuse.

5. Redesigned Waste-Water Heat Exchanger

The concept of employing a falling-film heat exchanger in the intended application is excellent because it is self-cleaning and because the waste-water heat transfer cannot be obtained economically by any other known passive methods. Furthermore, the potable-waterside heat transfer problems illustrated by the results of thermal analyses aforementioned can be solved by making better use of some of the available utility water pressure.

A section of the redesigned 5-foot long heat exchanger which corrects the problems discussed in Section 4 is shown in Figure 1. The inventor may wish to consider alternative designs.

The redesigned heat exchanger was analyzed and its effectiveness and pressure drop characteristics are given in Figure 2. At a mass-flow rate of 2 gpm, the overall conductance of the 5-foot long heat exchanger is 1227 Btu/hr-^{o}F. At this flow rate, 50.8% of the resistance is in the potable-water side and 49.2% of the resistance is in the falling-film side; this equality is considered to be optimal.

6. Manufacturer's Selling Price and Installation Costs

The cost of materials for the redesigned heat exchanger are $52 which includes $2 for the solder. This cost can be reduced 20% if the material is procured directly from the mill. Only semi-skilled labor is required to manufacture and assemble this heat exchanger. Labor is required to flatten the water tubing, coil it on a form, tank-solder the tubing to the central copper pipe, and epoxy-paint the assembled unit. The free ends of the water tubing must be reformed so as to interface with the remaining water tubing to which it is to be connected. From personal experience, a total labor time of 2 hours per heat exchanger is estimated to be required if quantity production is involved. At a semi-skilled labor cost of $8/hr, 100% manufacturing overhead, 20% G&A, and a 10% profit, the manufacturing selling price is calculated to be $111 per heat exchanger.

The wholesaler will markup the price 50% if the product sells well so that the cost to the builder is $166 per heat exchanger. If the architect designs the installation of the heat exchanger properly, installation costs should be minimal. At this time, insulation of the heat exchanger is not deemed necessary. Crediting six feet of sewer line which does not have to be supplied if the heat exchanger is installed, the net installation cost is estimated to be $50 including the builder's profit. Thus, the total investment per heat exchanger is $216.

7. Energy Savings and Simple Payback

Obtaining a believable value for hot water usage has proved to be frustrating.

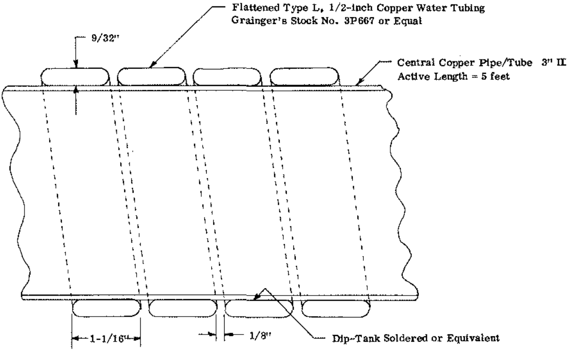

FIGURE 1

SECTION VIEW OF REDESIGNED HEAT EXCHANGER

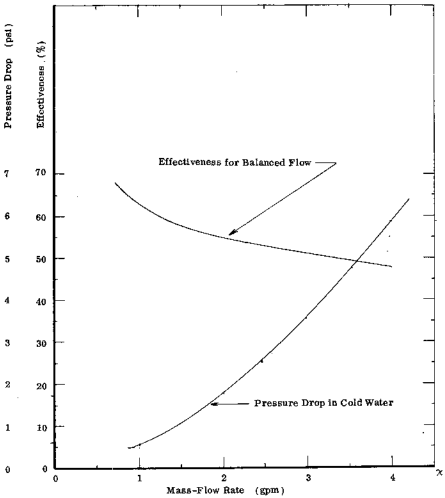

FIGURE 2

EFFECTIVENESS AND PRESSURE DROP FOR
REDESIGNED FALLING-FILM HEAT EXCHANGER

The Office of Technology Assessment has used a value of 105 gallons per day (gpd) for a single-family, four-person household (Reference 4); Tully (Reference 11) quotes a value of 75 gpd for a family of 4; Kreider and Kreith (Reference 8) quote a value of 87 gpd for a family of 4. It appears that the value quoted is determined by the temperature at which the hot-water tank is operated. To obtain a value for hot water usage, the following approach was taken.

Annual U.S. residential energy consumption during 1983 was 14.74×10^{15} Btu or 14.74 Quads (Reference 7). Reference 8 reports that 15.1% (others quote percentages of 13.4, 14.5, etc.) of this total consumption was used for water heating -- 2.23 Quads. If the thermostat on the hot-water heater is set at 120°F, if the average household usage is 87 gpd, and if the tap water temperature is taken at the national average of 55°F (Reference 8), then the average annual energy put into just heating the tap water is 1.72×10^{7} Btu per household. Multiplying this value by the 80 million residences excluding moblie homes (Reference 7) yields 1.37 Quads as the nation's energy consumption for heating tap water from 55°F to 120°F. To this amount must be added thermal losses and fuel energy conversion losses which are calculated to be 38.6% -- this is considered to be a reasonable value for these losses. Therefore, an average consumption of 87 gpd at a hot water temperature of 120°F and a tap water temperature of 55°F will be used herein.

The heat that can be recovered by the inventor's heat exchanger is a fraction of the 1.37 Quads needed to heat the water to 120°F. There are a number of reasons why this is true.

The inventor measured a drain-water temperature of 93°F during showering at a shower water temperature of 105°F. OERI estimated that the water temperature entering the heat exchanger was at 90°F and this appears to be very reasonable. The mass-flow rate of drain water is 30% greater than the mass-flow rate of the 120°F hot water for this case. Thus, the energy available for recovery in the waste water is 70% of the energy drained from the hot-water tank -- that is, the 1.37 Quads must be reduced to a recoverable 0.96 Quad on a national basis.

The main uses of hot water in the home are for bathing, clothes washing, and for dishwashing. Since the heat exchanger recovers energy only when waste water and tap water flow through it simultaneously, the use of devices which store hot water such as bathtubs and clotheswashers will not normally result in energy recovery. In the U.S., 71.4% of the households have clotheswashers, 36.1% have automatic dishwashers (require 140^{o}F water temperature), and almost all have showers or a combination of bathtubs and showers (Reference 7). On the assumption that the average household uses the washing machine twice a week (80 gallons of hot water per week), and one person uses the bathtub once a day (140 gallons per week), the recoverable energy is further reduced by 36% for those homes with washing machines and bathtubs -- conservatively, on a national basis, the above 0.96 Quad is further reduced to about 0.61 Quad (179 Billion KWH). This is not an insignificant amount of energy. The potential annual dollar saving for the 30.4% of the households which have electric hot-water heaters is $4.7 billion using a Kw-hr cost of 8.66 cents. Only about 25% of this potential saving can actually be realized because of heat exchanger effectiveness and because of the installation restrictions described below.

Finally, the use of the inventor's heat exchanger is restricted to those homes with basements because both its effectiveness and self-cleaning features require vertical orientation. Since 1970, somewhat more than 40% of new houses have been built with full or partial basements (Reference 7). Because slab construction has only become popular recently, it can be assumed that the inventor's heat exchanger is applicable to 50% of the nations households.

With regard to an average household, the annual energy required to just heat 55^{o}F tap water to 120^{o}F is 1.72×10^{7} Btu. Using the factors developed above, the recoverable energy in the waste water is 7.7×10^{6} Btu (2257 Kw-hr thermal). The estimated 120^{o}F mass-flow rate is between 1.4 and 2.5 gpm (Reference 8) which is translated to a waste water mass-flow rate between 1.8 and 3.3 gpm or an average of 2.5 gpm. At this average mass-flow rate, the redesigned heat exchanger effectiveness is 53% (Figure 2). Therefore, the recovered energy is 4.08×10^{6} Btu per year (1195 Kw-hr thermal).

The simple payback economics of the redesigned falling-film heat exchanger are summarized in Table 1 for the three most common energy fuel sources. The conversion efficiency for the natural gas water heater is based on the use of a fuel-efficient device (Reference 6). The energy costs are the current Baltimore Gas and Electric Company residential rates and the oil cost is the present estimated regional average cost.

Energy Source	Conversion Efficiency	Energy Cost	Dollar Savings per Year	Simple Payback in Years (Without Interest)
Electrical	100%	8.66¢/Kw-hr	103.49	2.09
Natural Gas	76%	$6.35/10^6 Btu	34.09	6.34
Oil	55%	$1.0/gallon	53.48	4.04

Notes: 1. Energy saving for an average household is 1195 Kw-hr thermal per year

2. Installed cost of heat exchanger is $216

TABLE I

SIMPLE PAYBACK SUMMARY FOR REDESIGNED THIN-FILM HEAT EXCHANGER

It should be noted that the payback years for the inventor's heat exchanger are significantly less than those for domestic solar hot-water systems (Reference 12). Even with a 40% tax credit, the payback years for a single-family house (4 occupants) equipped with a solar water-heating system is 6 years if it supplements an electric system, 12 years if an oil system is supplemented, and 16 years if a natural gas system is supplemented.

The installed cost for the retrofit market is estimated to be about $255. For homes with installed electric water heaters, the payback years will increase to about 2.5. For the 51.1% of the homes with gas water heaters (Reference 7), the average fuel conversion efficiency is estimated to be 65% (Reference 12) rather than the 76% efficiency used in Table 1. The payback years will not change. Many oil-heated homes are supplied with hot water by running the supply water through the furnace and then directly to the tap. These tankless systems are less efficient than the efficiency assumed in Table 1 because the furnace must operate all summer. The payback years are not expected to change from the value given in Table 1.

Sixty years ago, solar water heaters sold well in Florida to home owners with installed electric water heaters when their simple payback was about 2 years (Reference 8). The inventor should expect the same market response today when he offers his heat exchanger to home owners who have electric hot-water heaters.

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