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A naturally aspirated convector for domestic heating application with low water temperature sources

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ABSTRACT

The introduction of low temperature renewable energy sources such as geothermal heat pumps into domestic central heating systems will demand that new technologies be developed to dissipate the required heat loads into homes. The main reason for this is the lower operating temperatures associated with these energy sources, which can be as low as 35 °C and rarely exceed 55 °C. Unless the appropriate heat exchanger is deployed, expensive and intrusive alternatives such as forced air convectors, under floor heating and home insulation retrofitting must be considered. This work details the development of a turn-key heat pipe based naturally aspirated convector for domestic central heating applications. The results show that the heat pipe convector design has a power density of nearly 3 times that of a popular off the shelf panel radiator as well as a finned-serpentine convector. Furthermore, the low water content associated with the heat pipes results in a unit with a much reduced thermal response time which could be advantageous in the context of building thermoregulation.

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1. Introduction

Energy conservation is an important part of national energy strategies, whose growth in importance will continue into the future. This is due to the significant, if not crucial, role played by energy in the social and economical development of societies [1]. Geothermal heat pumps (GHP) have become a popular choice for new build homes as well as retrofitting older homes to ensure that renewable energy is acquired efficiently and cost effectively. GHPs operate by using the ground around a building as the heat source, or in some cases the ambient air. By installing a suitably sized GHP loop in the ground or in the air, heat energy can be taken from a low-temperature source and upgraded to a higher temperature at which it can be usefully employed for domestic heating purposes [2,3].

The conventional household hydronic-based radiator design has changed very little over the last hundred years. In these types of units the hot source water flow is channelled within the radiator housing. The hot fluid spreads across and heats a large enough internal surface area within the device that sufficient heat can be dissipated into the room air passively by buoyant natural convection and radiation. Newer devices operate on the same principle, though may include external fins to decrease the overall size and weight of the units.

With regards to the heat transfer, the main drawbacks of having the hot water flowing within a large internal volume are that the velocities are quite low causing a non-negligible thermal resistance on the water-side and the flow can be poorly distributed causing stagnation zones and large temperature variations across the radiator (see Fig. 1). Further to this the heat transfer is negatively influenced by the height of traditional radiators, which are typically well in excess of 50 cm. For panel radiators with rear vertically aligned fins, this height is longer than the length required for the thermal boundary layers on each opposing wall of the fin channel to merge. As a result, beyond this point the local driving temperature differential for heat transfer continually decreases, and so does the local heat transfer rates. This is not ideal from a convective heat exchanger design standpoint. Finally, the large water content would increase the thermal mass thus adversely affecting the transport delay in the radiator. The low thermal responsively would influence the performance and energy savings associated with systems with radiators controlled by thermostat valves (TRVs), for example [4].

Conventional radiators are not ideal for use in low temperature water heating systems, such as GHPs, which generally operate below 55 °C for one-stage conventional heat pumps. Their power densities are typically so low that oversized radiators would be required. A standard panel radiator output is given in Fig. 1. The unit is rated at 750 W for an operating temperature of 80 °C, though is found to underperform somewhat. At an inlet water temperature of 55 °C, which is rather high for a GHP, the output reduces to ~300 W meaning that two radiators would be required to perform

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Nomenclature

C_p	specific heat (J/kg K)
T	temperature (°C)
V	volume (m^3)
$\dot{V}$	volumetric flow rate (m^3/s)
ρ	density (kg/m^3)
Q	rate of heat transfer (W)
w_i	uncertainty in measurement
w_z	uncertainty in calculated result
x_i	measurement
Z	calculated variable

the equivalent task which negatively influences cost and occupies more space within the room. Preferable options in low temperature water heating systems are enhanced building insulation, under floor heating systems [5], or fan-based forced convection heat exchangers. In terms of retrofitting existing buildings neither the re-insulating nor the under floor heating options are attractive due to the large added cost and disruptive nature of the installation [6]. Fan-based convectors are beginning to hit the market for this application though retrofitting for electrical connections at water points, fan noise and long term reliability are ongoing concerns for retrofit domestic applications.

Heat pipes are hermetically sealed tubes containing a small amount of working fluid in a partial vacuum. The fluid exists in both the liquid and vapour phases. When the evaporator zone of the heat pipe is placed in a hot medium, the heat will be transferred to the working fluid through the pipe wall. The working fluid absorbs heat energy which is sufficient to convert the fluid from the liquid phase to vapour phase. The increased pressure in the hot end of the pipe forces the vapour to flow to the cooled end of the pipe. Here the vapour condenses releasing the heat that was absorbed in the evaporator end. This region is termed the condenser. The heat is then transferred across the tube wall of the condenser end and is dissipated to the ambient surroundings by various forms of convection, depending on the application. In many applications where heat is transferred to or from fluids, fins are attached to the outer surface of the heat pipe in order to improve the heat transfer capability of the heat pipe. Within the pipe the condensate liquid returns to the evaporator end of the heat pipe where it is again evaporated. Since the latent heat of evaporation is large, considerable quantities of thermal energy can be transported very effectively with a very small temperature differences from end to end.

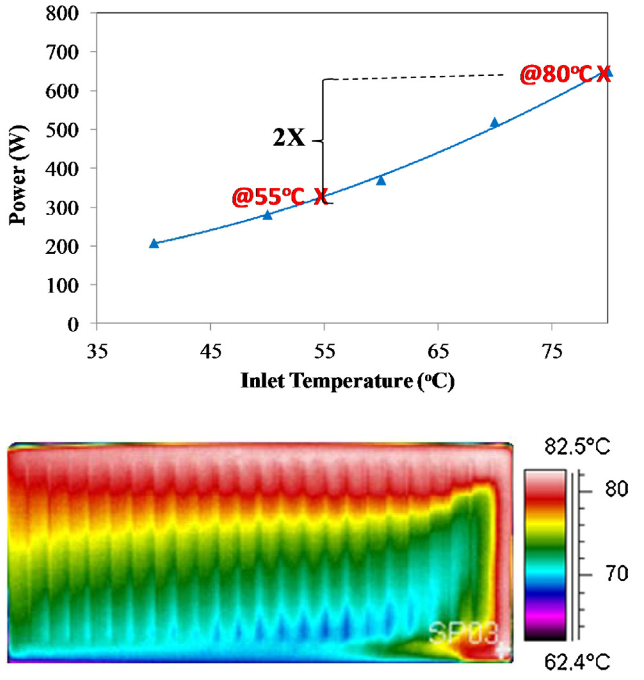

Fig. 1. Heat transfer (top) and thermal image (bottom) of a popular panel radiator.

Heat pipes are categorized depending on the way the condensate working fluid in the heat pipe returns from the condenser to the evaporator of the heat pipe. Capillary driven or wicked heat pipes use a wick structure to return the condensate and can operate in any position. Gravity assisted heat pipes, often called closed thermosyphons, rely on the force of gravity and must be operated with the evaporator end below the condenser end. Unlike conventional heat exchangers, heat pipes do not require external pumping, are low cost, passive, reliable, robust and hugely effective transporters of heat. Heat pipes are often referred to as thermal superconductors because they can have effective thermal conductivities that are 50–500 times higher than copper.

Heat pipe technology has a proven track record in space technology [7,8] thermal storage [9,10], harnessing of renewable energy [11,12] and in waste heat recovery of various processes [13,14]. As in domestic air conditioning systems, their advantages and economics are proven [15] with an expanding number of applications which utilize such technology to ensure that heat energy is transferred effectively [16–18]. Heat pipes have also been considered for heat collection from various sources for domestic heating applications [19,20].

The primary objective of this research is to design, construct and test a naturally aspirated heat pipe based convector demonstrator that would be suitable for GHP retrofit installations. The overarching objective is to construct a demonstrator technology that mitigates the need for expensive and disruptive building retrofits, such as re-insulating the home and/or installing under floor heating. Specifically, the objective is to reach a heat transfer rate of 750 W with an inlet water temperature of 55 °C and do so in a much reduced space compared with conventional panel radiators and finned serpentine convectors.

2. Design and manufacture

2.1. Design concept

The design concept of the heat pipe based convector is given in Fig. 2. The heat exchanger is comprised of two naturally aspirated air side tube bundles whose fins are heated by being in thermal contact with the condenser ends of six heat pipes (per side). The heat pipes are press fit to the aluminium fins in a staggered arrangement. In order to increase the heat transfer per channel the fins are wavy, as depicted in Fig. 3.

Heat is absorbed into the heat pipes at a centrally located hot water manifold. The evaporator ends are immersed in the flow of hot water which is routed through a serpentine channel to increase the water side heat transfer coefficient. The heat pipe evaporator ends are fitted with annular copper fins and are arranged in a cross flow arrangement with four heat pipes per channel (two per side).

2.2. Simulation driven design

Simulation Driven Design was used to determine the geometric aspects of the fins and channels within which the air flows. A commercial CFD package was utilized to model one half of a single 3D channel and various arrangements (heat pipe spacing, channel width, etc.) were simulated until enough heat was transferred per channel that the overall size of the heat exchanger was acceptable.

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