Simulation Modelling Practice and Theory 19 (2011) 1154–1163

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Heat pipe-based radiator for low grade geothermal energy conversion in domestic space heating

K. Kerrigan [a], H. Jouhara [b,1], G.E. O'Donnell [a], A.J. Robinson [a,*]

[a] Department of Mechanical & Manufacturing Engineering, Parsons Building, Trinity College Dublin 2, Ireland
[b] School of Engineering and Design, Brunel University, Uxbridge, Middlesex UB8 3PH, UK

ARTICLE INFO

Article history:
Received 16 October 2009
Received in revised form 21 May 2010
Accepted 31 May 2010
Available online 8 June 2010

Keywords:
Heat pipe
Heat exchanger
Design

ABSTRACT

A severe technical drawback of geothermal heat pumps (GHPs) is the fact that the nominal operating temperature available for domestic space heating is typically in the region of 50 °C. This is 25–40 °C less than conventional boiler settings used in hydronic central heating applications. As a result, GHPs are not generally ideal for direct replacement of conventional hydronic central heating systems because of the low relative distribution temperatures unless extreme measures are taken to improve the thermal insulation of the buildings. A preferable option for GHPs is underfloor heating. In terms of retrofitting existing buildings neither the re-insulating nor the underfloor heating options are attractive due to the large added cost and disruptive nature of the installation. As such, very high performance low temperature radiators that are pluggable into existing hydronic central heating systems are a major enabling technology for this sustainable energy source. In this investigation a Simulation Driven Design technique was utilized to develop a novel low water content and high thermal throughput heat pipe-based radiator. The radiator was subsequently fabricated and tested and showed an exceptionally high power density and very fast response time compared with conventional wet radiators.

1. Introduction

Conventional heat exchangers (HEXs) for hydronic central heating applications have changed very little over the past one hundred years or more. In these types of units, the hot source water flow is channelled within the HEX. In this way, hot fluid comes into contact with a large enough internal surface area within the device to allow the required amount of heat to be dissipated passively into the room 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. The main drawbacks of having the hot water flowing within a large internal volume are: that the devices are unnecessarily large and/or must operate with high source water temperatures, typically above 70 °C [1]; the water cools as it crosses the HEX causing large temperature variations across it (the cooler regions dissipate less heat requiring the HEX to be longer to achieve rated power); due to the very slow moving water within the HEX, the air which is dissolved within the water collects within the device forming air pockets. These air pockets have the effect of making the effective heat dissipating area smaller i.e. operating below design specification, requiring frequent bleeding to dispel the air. Finally, the combination of the fact that the surface area must be large enough to reach a given power dissipation and that the entire unit must have a built strength to withstand over 8 bar operating pressure results in very heavy HEXs that has the negative influence of taking a substantial time to heat to

* Corresponding author. Tel.: +353 1 856 3919.
E-mail addresses: hussam.jouhara@brunel.ac.uk (H. Jouhara), arobins@tcd.ie (A.J. Robinson).
[1] Tel.: +44 1895 267656; fax: +44 1895 256392.

1569-190X/$ - see front matter © 2010 Published by Elsevier B.V.
doi:10.1016/j.simpat.2010.05.020

operating temperature/power level. The large mass of material combined with the large volume of water has a major adverse impact on start-up as well as the thermostatic control capability and room comfort.

Conventional radiators are not ideal for use in geothermal heat pump (GHP) domestic heating applications because of the low source water temperatures generated. The power densities are typically so low that massively oversized radiators would be required. A preferable option for GHPs is enhanced building insulation or under floor heating systems. 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 [1].

Building legislation and environmental concerns [2–4] are driving designers of building services and air conditioning systems towards more energy efficient solutions such as heat pipes. Heat pipe technology has proven track records in space technology [5,6], thermal storage [7,8], harnessing of renewable energy [9,10] and in waste heat recovery of various processes [11,12]. In domestic air conditioning systems, its advantages and economics are proven [13] with an expanding number of applications, which utilise such technology to ensure that energy is transferred in an efficient way [13–15].

In the current investigation a novel high power density radiator for hydronic central heating applications has been developed that utilizes heat pipes. A heat pipe is a hermetically sealed tube that contains a small amount of fluid, which exists inside the heat pipe shell as vapour and liquid at equilibrium [16]. When heat is applied at one end of a heat pipe the liquid within it evaporates. The heat transfer rate within the wick structure is extremely high as it is a combination of conduction across a very thin saturated metallic wick and or nucleate boiling [17]. The vapour which is generated at the heated end spreads to the cooled end of the heat pipe. Here the extraction of energy causes the vapour within the heat pipe to condense back to a liquid phase thus releasing the heat that was absorbed at the heated region albeit at a different location, i.e. at some location remote from the heated end. A porous wick structure wrapped around the inner wall of the heat pipe draws the liquid condensate back to the heated section where it is once again vaporized. In the current investigation, water was chosen as the working fluid and copper as the shell material. As water and copper are chemically compatible, no generation of non-condensable gasses (NCGs) will be taking place within the heat pipe [18,19]. The generation of NCGs typically has an adverse affect on the performance of a heat pipe as the NCGs accumulate in the condenser section of the heat pipe subsequently reducing the length of heat pipe capable of releasing the latent heat of vaporisation.

To achieve the power density required for effective heat dissipation from low grade geothermal heat sources a Simulation Driven Design technique was implemented which utilized commercial computational fluid dynamics (CFD) software to model the convective and radiative heat transport of a single channel of the finned heat pipe tube bundle immersed in otherwise quiescent room temperature air. The purpose of the CFD simulations in this work was therefore to accelerate the design process by allowing multiple geometric configurations to be considered in terms of single phase air side heat transfer capabilities. This meant that while experimental works were later carried out to ensure the validity of the final design, the effectiveness of that final design relative to other pipe configurations and fin spacings could be considered prior to the prototyping/experimental phase of the work. The radiator as well as a test facility was subsequently fabricated and the results compared favourably with simulations. Further, the steady and transient responses were tested against a standard commercially available radiator to illustrate the improved thermal performance.

2. Design concept

The design concept of the heat pipe-based radiator is given in Fig. 1. As illustrated in the figure, one end of the heat pipes is immersed in the flow of hot source water at the collector end of the HEX called the hot water manifold. Here the heat energy of the hot source water flow is absorbed into the six heat pipes by vaporising the water inside them. Since they are under a partial vacuum the water within them boils at a temperature that is lower than the source hot water temperature.

As depicted in Fig. 1 there are dividing plates within the manifold which force the water over the collector ends of the heat pipes within a serpentine channel for improved thermal energy transfer. The steam generated inside the heat pipes at the collector end flows away from the collector region of the heat pipes to the heat ejector end. Here it condenses on the inner wall of the heat pipes releasing the heat at a location which is remote from where it was absorbed. In the heat ejector region the outer surface of the heat pipes are fitted with simple metallic fins (i.e. surface extensions) to achieve the necessary power dissipation for the given operating temperature. In the heat ejector region, referred to as a finned tube bundle, the location of the heat pipes and the spacing between the fins has been designed for optimal heat transfer by buoyant natural convection and thermal radiation.

3. Simulation Driven Design

Due to the complex nature of the flow and heat transfer within the finned tube bundle, conventional correlations for natural convection are not sufficiently accurate for design purposes. This being the case, a Simulation Driven Design (SDD) technique was implemented whereby the commercial CFD package ANSYS CFX was utilised to simulate the coupled flow and heat transfer within a single channel of the fin bank. The physical domain in this analysis incorporates the assumed isothermal condenser section of the heat pipe(s), the metallic fin attached to the heat pipe and the section of air between the fins and surrounding the heat pipe(s). The isothermal nature of the heat pipes, the repetitive nature of the fin spacing, in