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Original Research Article

Heat transfer in a U-Bend pipe: Dean number versus Reynolds number

Christopher G. Cvetkovski [a], Stanley Reitsma [b], Tirupati Bolisetti [c,*], David S.K. Ting [a]

[a] Turbulence and Energy Laboratory, Ed Lumley Centre for Engineering Innovation, University of Windsor, Windsor, Ontario N9B3P4, Canada
[b] Geosource Energy, 1508 Hwy 54, Caledonia, Ontario, Canada
[c] Department of Civil and Environmental Engineering, Ed Lumley Centre for Engineering Innovation, University of Windsor, Windsor, Ontario N9B3P4, Canada

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ABSTRACT

The performance of ground source and surface water heat pumps relies greatly on the heat transfer efficiency throughout the ground loop configuration. Typically these are vertical loops and consist of two pipes connected by a U-Bend at the bottom end. The U-Bend section generates vortical structures and turbulence, enhancing the heat transfer process. Two parameters that affect the flow turbulence and vortical structures are the Reynolds number and the Dean number. The isolated effects of the Reynolds and the Dean number are studied. It was found that while the Reynolds number has the greater effect on the average heat flux of the system; the Dean number's influence on the heat flux is greater in the curved section of the pipe. The large vortex structures can last for many diameters downstream of the U-Bend. For the high Reynolds number flow it was shown that increasing the Dean number significantly enhances the longevity of vortex structures. This indicates that enhancing the Dean number in an already turbulent flow will further augment the heat transfer process.

1. Introduction

Ground source heat pumps (GSHPs) and surface water heat pumps (SWHPs) are a means to extract or reject energy from or to the earth for heating and cooling purposes. A typical GSHP system, as shown in Fig. 1, consists of a reversible heat pump, the building ductwork and the ground loop. The SWHPs also work similar to the GSHPs except that they draw/discharge heat from/to surface water sources. The heat pump acts as a reversible vapour-compression refrigeration loop [1,2] so that the system can be reversed for the different seasonal modes. A pump delivers a pretreated working fluid to effect the heating or cooling of the indoor building environments [3]. A group of ground source heat pumps can be linked together to form a geothermal energy field where each system works in parallel to manage thermal requirement for large buildings. There are many types of ground source heat pumps available to the consumer and each has its own advantages and disadvantages. Vertical ground source heat pumps are the most common and they employ a vertical pipe loop underground as opposed to a horizontal or helical configuration [4]. These vertical pipe loops can often reach depths of 100 m. With the relatively constant ground temperature [5–7], the vertical ground loops provide an advantage with a more predictable performance in the heat transfer process [8,9]. Since these vertical systems go straight into the earth they require boreholes to be dug to the length that is required. The cost of this digging exponentially rises with the depth resulting in tens of thousands being spent on the installation. Overestimation and rough modelling of the systems size and performance are the cause of the large capital needed [4]. Thus there is a strong need to better understand the heat transfer between the working fluid, the pipe wall and the surrounding environment under different conditions. Currently the models that are employed in design and GSHP software are analytical and approximate [10,11]. Since the detailed flow structures and turbulence within the loops can have a significant effect on the rate of heat transfer, they should be properly included and simulated using computational and numerical methods [12–15].

In vertical pipe loop setups, there exists a U-Bend section of pipe that returns the working fluid back to the surface. This U-Bend can generate secondary flows called the Dean vortices in addition to flow turbulence which are known to enhance heat transfer [16–21]. The Dean number is the product of the Reynolds number (Re) and the square root of the radius of the pipe (r) over the bend's radius of curvature (Rc) and can be expressed as:

$$Dn = Re\sqrt{\frac{r}{Rc}} \qquad (1)$$

* Corresponding author. Tel.: +1 519 253 3000x2548.
E-mail addresses: chris@cvetkovski.ca (C.G. Cvetkovski), sreitsma@geosourceenergy.com (S. Reitsma), tirupati@uwindsor.ca (T. Bolisetti), dting@uwindsor.ca (D.S.K. Ting).

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Nomenclature

C_{des}	detached eddy simulation constant
C_p	specific heat capacity, J K^{-1}
C_μ	eddy viscosity constant
D	diameter, m
Dn	Dean number
G_b	generation of turbulent kinetic energy due to buoyancy, J kg^{-1}
G_{k1}	generation of turbulent kinetic energy due to mean velocity, J kg^{-1}
g	gravitational acceleration, m s^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
k_1	turbulent kinetic energy, J kg^{-1}
l_{des}	length scale for detached eddy simulation, m
r	radius, m
Rc	Radius of curvature, m
Re	Reynolds number
S_{k1}	turbulent kinetic energy source term, J kg^{-1}
S_ε	dissipation rate source term
T	temperature, K
V	Velocity, m s^{-1}
x	number of diameters (D = 0.0254 m)
Y_k	dissipation rate of k
Y_M	partial dissipation rate due to fluctuating dilation of compressible turbulence

Greek symbols

Δ	change
ε	dissipation rate
μ	dynamic viscosity, Pa s
μ_t	eddy viscosity, Pa s
v	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
φ	radial position of U-Bend
Ω	vorticity, s^{-1}

Subscripts

cur	curved section property of pipe
in	inlet property
st	straight section property of pipe
wall	complete wall property

In pipe flow, such as that encountered in ground source heat pumps, the heat transfer between the wall and the fluid is predominately convective. The bottleneck of the heat transfer is the inner boundary layer, where a no-slip condition implies conduction behaviour. This bottleneck is more significant when the flow is laminar. Promoting flow turbulence reduces the bottleneck and enhances the convection process [22,23]. Over the narrow range of temperatures involved in low temperature geothermal processes, the fluid properties such as the Prandtl number remain relatively unchanged. As such the convective heat transfer is primarily a function of the Reynolds number in a straight pipe. For a pipe with a U-Bend, the effect imposed by the Dean number also becomes important.

Florides and Kalogirou reviewed the current state of ground source heat pumps up until 2006 [10]. The general conclusions included increasing GSHP performance with increased flow velocity when using smaller pipes and the line source model is the standard analytical approach for evaluating the characteristics of the borehole. However, it does not comment on the analytical models' accuracy with respect to the much more detailed numerical methods, such as the finite volume techniques used in this study. More recently Philippe et al. [11] investigated the three main analytical models (infinite line source, infinite cylindrical model, and finite line source) and tested the validity ranges for maximum accuracy. The infinite line source model which applies Lord Kelvin's heat source equations to GSHPs was developed in 1948 by Ingersoll

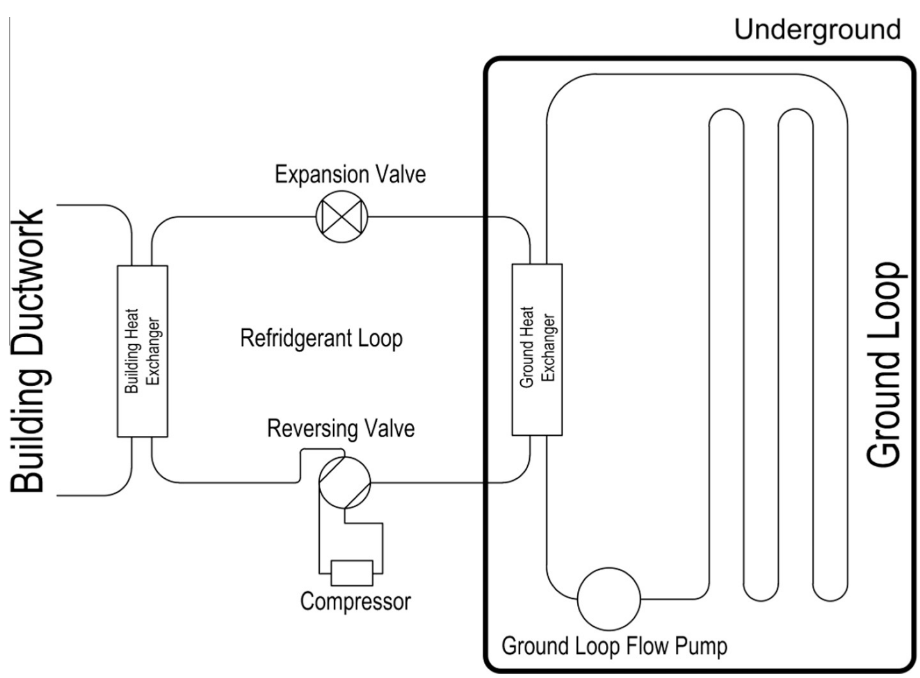

Fig. 1. Typical ground source heat pump system.

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