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Heat transfer and pressure drop in annuli with approximately uniform internal wall temperatures in the transitional flow regime

Dickson D. Ndenguma, Jaco Dirker *, Josua P. Meyer

Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, South Africa

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ABSTRACT

An experimental study was conducted to determine the lower and upper Reynolds number limits of the transitional flow regime, and the characteristics of the heat transfer coefficients and friction factors for annular passages with different hydraulic diameters and diameter ratios in the transitional flow regime. Water was used in this investigation during isothermal, heating and cooling cases. Four horizontal concentric counter-flow tube-in-tube heat exchangers with conventional inlet geometries were considered to obtain the required data. The flow was both hydrodynamic and thermally developing, and the transitional flow was composed of mixed and forced convection types. The wall temperature on the inner surface of the annular passages was approximately uniform, while the outer surface was isothermal. Average Nusselt numbers were obtained for both the heating and cooling cases, while friction factors were obtained for heating, cooling and isothermal adiabatic conditions. Isothermal adiabatic condition was considered for reference purposes. The geometric size of the annular passage and direction of the heat flux (heating and cooling cases of annular fluid) had a significant influence on the heat transfer coefficients, friction factors and Reynolds number span of the transitional flow regime. The annular geometric parameters that represent the geometric size of the annular passage were proposed and found to describe the heat transfer coefficient and friction factors well. Subsequently, correlations for predicting the Nusselt numbers and friction factors in the transitional flow regime were developed.

1. Introduction

Flows in annular passages are of interest to thermal engineers due to their wide range of applications, including their importance in, for instance, tube-in-tube heat exchangers, which are commonly found in several industries. The fluid in the annular passage may either be heated or cooled, depending on the temperature gradient in relation to the heat transfer surface. Different thermal boundary conditions may exist at the heat transfer surface, which influence the heat transfer and pressure drop characteristics, especially if thermal boundary conditions have an impact on buoyancy-driven secondary flow within the passage.

In literature, most investigations are carried out for either uniform wall heat flux or uniform wall temperature conditions [1]. Uniform heat flux conditions are prevalent in solar heating, electric heating, electronic cooling and drying technology. Uniform wall temperature conditions are, for instance, relevant to boilers and condensers where one of the fluids undergoes a phase change at the saturation temperature associated with the operating pressure within the relevant heat exchanger flow path. Some familiar engineering applications that involve condensation and boiling are found in refrigeration and steam power plants.

Heat exchangers are often designed to operate in either the laminar or turbulent flow regimes and not in the transitional regime. This could be due to a lack of knowledge of behaviour in the transitional flow regime, or due to an operating condition requirement, or due to the fact that designers want to increase heat transfer coefficients by choosing turbulent flow regime operating conditions. However, due to several reasons, including energy requirements and design and operating constraints, heat exchangers may end up being operated in the transitional flow regime [2–9].

During the thermal design stage of a heat exchanger, correlations are needed to describe the heat transfer coefficient and the friction factor in order to estimate its required geometric size to sustain a desired heat transfer and fluid flow rate. For fully developed forced convection flow in the laminar regime, temperature and fluid flow distributions could either be derived theoretically, or obtained experimentally or determined numerically for some boundary and geometrical cases. For the turbulent flow regime

* Corresponding author at: Department of Mechanical and Aeronautical Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa.

E-mail address: jaco.dirker@up.ac.za (J. Dirker).

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Nomenclature

a	annular diameter ratio (D_1/D_o)
A_c	cross-sectional area
A_s	surface area
C, C_{iso}, C_d	coefficients
c_p	specific heat
D	diameter
F	factor to take into account the dependence on a
f	friction factor
Gr	Grashof number
h	convection heat transfer coefficient
K	factor to take into account the temperature dependence of fluid properties
k	thermal conductivity
L_{dp}	pressure drop length
L_{hx}	heat exchange length
m	correlation exponent
$\dot{m}$	mass flow rate
Nu	Nusselt number
n	correlation exponent
Δp	pressure drop
Pr	Prandtl number
$\dot{Q}$	heat transfer rate
Re	Reynolds number
Re_1	lower Reynolds number limit of the transitional flow regime
Re_2	upper Reynolds number limit of the transitional flow regime
Ri	Reynolds number
T	temperature
$\overline{T}$	average temperature
V	average cross-sectional velocity
z	correlation exponent for the viscosity ratio

Greek symbols

ρ	density
μ	dynamic viscosity
λ	annular geometric parameter

Subscripts

0	inner wall of outer tube
1	outer wall of inner tube
iso	isothermal
b	bulk fluid property
ca	cooled annulus
d	diabatic
h	hydraulic
ha	heated annulus
i	inner flow passage
in	inlet
iw	inner tube wall
LMTD	logarithmic mean temperature difference
o	annular flow passage
out	outlet
ow	outer tube wall

conditions, this can be achieved by correlating experimental or numerical data [10]. However, for the transitional flow regime, data can only be obtained via experimental means, which is often difficult to perform. Therefore, to some extent, the transitional flow regime characteristics have not yet been documented sufficiently to enhance the accuracy of the relevant heat transfer and pressure drop predictions during the design phases of a system.

In terms of laminar and turbulent flow conditions, several research efforts have been undertaken to investigate heat transfer and pressure drop behaviour in annular passages with different hydraulic diameters and annular diameter ratios. Some of the main purposes of these studies were to specifically determine the effect of the annular diameter ratio, as well as to develop correlations that could best describe the thermal and flow performance of an annular passage in terms of the annular ratio [11–15]. Due to the relatively high heat transfer coefficients obtained during turbulent flow, most of the literature references in this regard are available for turbulent flow cases. In addition, fully developed flow under pure forced convection conditions is often assumed [1].

Among several operating state parameters, the direction of heat transfer has been reported to influence the heat transfer and pressure drop characteristics in a flow passage. This is evident from the well-known Dittus-Boelter correlation [16] for circular tubes where the exponent of the Prandtl number is selected according to the heat transfer direction. For annular flow passages specifically, little research has been conducted on this topic, but some data have been produced by Van Zyl et al. [15] and Prinsloo et al. [14] who investigated the effect of the heat transfer direction (from the inner wall to the annular fluid and vice versa) on the heat transfer coefficient and pressure drop in the turbulent flow regime of annuli of horizontal tubes. It was found that the direction of heat flux (or the relative wall to free stream fluid properties) had an effect on both the heat transfer and friction factor, which could be due to temperature differences between the inner wall and the annular fluid for the heated and cooled cases.

An aspect that complicates flow in the laminar and transitional flow regimes is the impact of buoyancy-driven flow, which may result in mixed convection scenarios where natural convection effects are significant enough to impact the heat transfer and pressure drop characteristics in a flow passage. Buoyancy-driven secondary flow often enhances the mixing of the fluid and improves its convective heat transfer ability. Existing results on mixed convection in a horizontal concentric annulus are derived mainly from theoretical studies for laminar flow conditions. These include work by Hattori [11], Nguyen et al. [17], Islam et al. [18], Mirmasoumi and Behzadmehr [19], Mokhtari et al. [20] and Izadi et al. [21]. For experimental studies, only a few references are available in the literature. These include work by Mohammed et al. [22], Ciampi et al. [23] and Lu and Wang [24,25]. Some of these are briefly discussed here.

For instance, Mohammed et al. [22] conducted a study of mixed convective heat transfer for thermally developing and fully developed laminar air flow in horizontal concentric annuli in the thermal entrance length. They used an inner stainless steel tube, operated at a uniform wall heat flux boundary condition, while the outer wall of the annulus was adiabatic. The effect of secondary flow was found to be significant and gave higher local Nusselt numbers compared to cases without secondary flow. Another important observation was that the heat transfer coefficients for thermally developing flow were considerably greater than the corresponding fully developed flow values over a significant portion of the annulus.

In their studies, Lu and Wang [24,25] experimentally considered the characteristics of a developing flow with buoyancy-