The Effect of Eccentricity in Fully Developed Annular Pipe Flow on the Convection Heat Transfer and Darcy Friction Factor

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Abstract

Eccentricity in annular channels contributes to changes in fluid flow characteristics which in turn, affects the performance and integrity of the configuration. This research investigates a model of an annular channel with a diameter ratio of 0.762, an aspect ratio of 68.9:1 and heating of the internal surface of the inner cylinder with a 1.105MW/m2 heat flux. The Reynolds number ranges from 5,000 to 85,000 and non-dimensional eccentricity (e*) ranges from 0 to 0.92. The results have shown gradual, but significant changes, as the eccentricity is increased. The resulting velocity and temperature profiles significantly affected the Darcy friction factor, convective heat transfer coefficient, and Nusselt number. This study was conducted, in part, to support an ongoing project to implement a design change for a 2nd-generation irradiation target holder at the High Flux Isotope Reactor (HFIR) of Oak Ridge National Laboratory (ORNL).

Introduction:
Annular flow has shown to have different turbulent boundary layer characteristics [1] compared to pipe flow. The differences emerge from the nature of the curvature of the inner wall of the annular flow. Studies show that a boundary layer on the inner wall of the annular flow has smaller turbulent kinetic energy than the outer wall for the same volume [2]. This study initially investigates the effect of water flow on the Darcy friction coefficient (hereafter referred to as friction factor or f).
where Δp is the pressure drop determined by flow simulation using turbulent flow models in the COMSOL Multiphysics® software, ρ is the density of the water coolant flow, D_e is the equivalent (or hydraulic) diameter of the annular pipe, with length L and average velocity $\bar{U}$. The simulations are conducted for Di/Do ranging from 0.76 to 0.90 at Re ranging from5,000 to 85,000. These results are compared with circular pipe friction coefficient using both Moody's chart and the following explicit correlation (Romeo et al., 2002):
Another key objective is to study the effect of eccentricity upon the surface temperature variation in the radial and streamwise directions. The overall flow changes affect the heat transfer coefficient, thus affecting the heat transfer within the channel. To analyze the changes, the Nusselt number is calculated and compared to both the empirical calculations and previous studies. Prior research in this field is limited; hence, this study is important to achieve confidence in our results going forward.

USE OF THE COMSOL MULTIPHYSICS® SOFTWARE:
The modeling of annular flow in this study relied primarily on the COMSOL Multiphysics® software. Turbulent flow models in the COMSOL® software, such as k-ϵ and SST, are used in this work to simulate the flow. The results are then coupled with the heat transfer module to study the surface temperature and the cooling effect of the configuration. A swept mesh was built by first starting with a cross-sectional area and specifying a physics-based, and automated extremely fine element size, and an unstructured, free triangular element type, for a total of 675 finite elements. Then the cross-sectional area mesh is swept in the axial direction to yield a final total of 1,507,950 elements. The solution process is controlled by a parametric sweep, using the annular eccentricity is varied parameter, and arriving at a stationary solution for each eccentricity value. The boundary conditions imposed are an inlet velocity of 4.87 m/s, an outlet pressure of 360 psi, and a uniform heat flux of 1.105 MW/m2 applied to the inner surface of the flow annulus.

Results:
The pressure drop is used to arrive at an equivalent friction factor using the Darcy-Weisbach formula and compared pipe flow friction factor using Moody's chart and empirical solution using the Romeo et al. The comparison between the simulated annular flow, and similar pipe flow, for the same Re and hydraulic diameter (De) shows a higher friction factor in the case of annular flow (Table 1). Furthermore, an increase in eccentricity also resulted in a small decrease in overall pressure drop.
The velocity profile of the channel is also impacted by an increase in the eccentricity. As the eccentricity increases and the gap between the two cylinders narrows, the flow rate in the narrower gap is reduced due to the increased resistance of flow passage. In the most eccentric case, the flow in the narrow gap yields approximately 11% of the maximum velocity of the larger gap (Figure 2). This impacts the heat convection process and it may produce unfavorable surface temperature on the narrow side. This flow reduction due to higher eccentricity can be seen in Figure 3.

Conclusion:
A computational study of the effect of eccentricity for turbulent fluid flows in eccentric, annular cylinders is conducted. The model geometry consisted of two cylinders, with the inner cylinder solved by parametric sweep of varying eccentricity. A gradual, but significant, impact in the results is evident as the eccentricity was increased for: velocity, pressure and temperature profiles (which directly affect the Darcy friction factor), and convective heat transfer coefficient (Nusselt number). Further analysis is required to refine the impact of the eccentricity on the local surface temperature and average Nusselt number.

Reference

[1] Itaru MICHIYOSHP & Tsuyoshi NAKAJIMA (1968) Fully Developed Turbulent Flow in a Concentric Annulus11, Journal of Nuclear Science and Technology, 5:7, 354-359, DOI:10.1080/18811248.1968.9732470

[2] Seo Y. CHUNG, Gwang H. RHEE, and Hyung J. SUNG (2002)Direct Numerical Simulation of Turbulent Concentric Annular Pipe Flow: Part 1: Flow field, International Journal of Heat and Fluid Flow 23.4: 426-440, DOI:10.1016/S0142-727x(02)00140-6

[3] Eva ROMEO, Carlos ROYO, Antonion MONZON (2001) Improved Explicit Equations for Estimation of the Friction Factor in Rough and Smooth Pipes, Chemical Engineering Journal, 369-374, DOI:10.1016/S1385-8947(01)00254-6

Figures used in the abstract

Table 1: Comparison of Darcy friction factor (*f*)

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Re	Darcy Weisbach (*f*)	Moody's Chart (*f*)	Romeo et al. (*f*)
5,254.77	0.04212	0.0364	0.0370
17,334.70	0.03008	0.0266	0.0269
29,414.62	0.02556	0.0237	0.0236
41,494.55	0.02306	0.0214	0.0218
53,574.48	0.02153	0.0202	0.0206
65,654.41	0.02045	0.0198	0.0197
77,734.33	0.01962	0.0189	0.0190

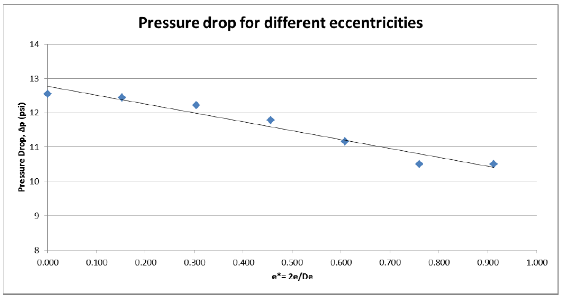

Figure 1: Linear relationship of dimensionless eccentricity values vs pressure drop.

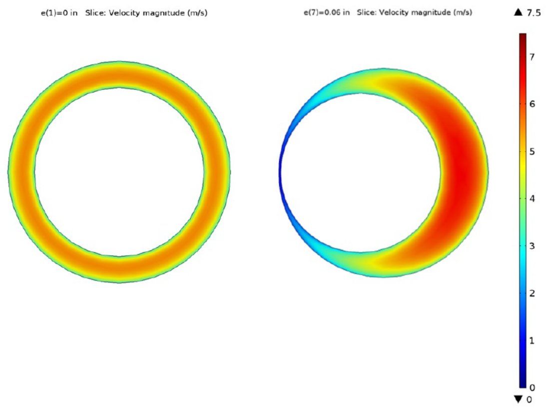

Figure 2: Velocity magnitude profiles for concentric annulus vs the most eccentric annulus case e*=0.92.

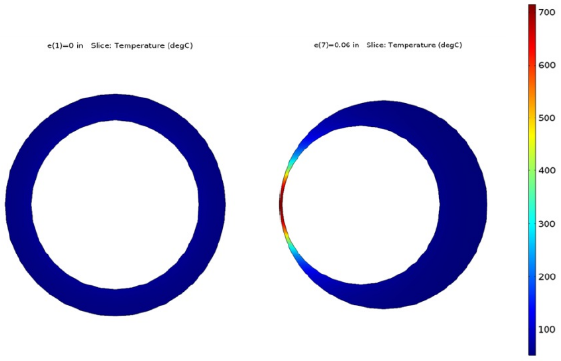

Figure 3: Temperature profiles at the pipe's outlet surface (length 0.965m) for concentric annulus vs. high eccentricity annulus case e*=0.92.