Transpirational heat and momentum transfer from a rotating cylinder

by Robert John Spannuth

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Chemical Engineering
Montana State University

Abstract:
In this investigation, heat transfer and moment coefficients were determined with and without transpiration mass transfer for a rotating cylinder in a finite medium with turbulent flow. Reynolds numbers ranged from 27,000 to 330,000. Mass transfer rates expressed as the ratio (Formula not captured by OCR) ranged from 250 to 35,000.

For the case of no mass transfer, moment coefficients were in excellent agreement with published data; however, there is no published data for heat transfer coefficients in the range of Reynolds numbers used in this experiment. In the moment coefficient experiment an apparent flow transition was observed at a Reynolds number of 55,000.

With transpiration, heat transfer and moment coefficients increased . with mass transfer. This phenomenon is consistent with the hypothesis that a laminar sublayer does not exist on the surface of a rotating cylinder for turbulent flow. The most significant result of this investigation is that the heat transfer coefficients increased much more dramatically with Injection than did the moment coefficients.

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FROM A ROTATING CYLINDER

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ABSTRACT

In this investigation, heat transfer and moment coefficients were determined with and without transpiration mass transfer for a rotating cylinder in a finite medium with turbulent flow. Reynolds numbers ranged from 27,000 to 330,000. Mass transfer rates expressed as the ratio V_{θ_o}/V_{r_o} ranged from 250 to 35,000.

For the case of no mass transfer, moment coefficients were in excellent agreement with published data; however, there is no published data for heat transfer coefficients in the range of Reynolds numbers used in this experiment. In the moment coefficient experiment an apparent flow transition was observed at a Reynolds number of 55,000. With transpiration, heat transfer and moment coefficients increased with mass transfer. This phenomenon is consistent with the hypothesis that a laminar sublayer does not exist on the surface of a rotating cylinder for turbulent flow. The most significant result of this investigation is that the heat transfer coefficients increased much more dramatically with injection than did the moment coefficients.

I. INTRODUCTION

Transpiration from a surface, that is, the existence of a velocity normal to the surface due to mass transfer, occurs in heterogeneous catalysis, combustion and evaporation at low pressures or near the boiling point. Other examples of transpiration include cooling of aerodynamic surfaces in high speed flights, cooling of turbine blades, and cooling of rocket nozzles. The objective of this investigation was the study of transpiration from a rotating cylinder in a finite medium with possible application in the cooling of shafts. Other applications may include the use of a rotating cylinder as a blender, spray applicator, or chemical reactor.

Early research on transpiration dealt with flat plates. Pioneer papers include the theoretical studies of Rubesin (1) and Dorrance and Dore (2) and the experimental work of Mickley et al. (3) in the 1950's. Since 1960 many contributions have been made with a major contributor being W. M. Kays (4). Mass transfer from a flat plate is discussed in Bird, Stewart, and Lightfoot (5). By comparison there are relatively few investigations of transpiration with geometries other than flat plates. Elzy and Wicks (6) and Johnson and Hartnett (7) have studied mass transfer from a stationary cylinder in crossflow. Cozart (8) has investigated transpiration from a rotating disc. Erickson et al. (9) have studied theoretically mass transfer from a moving, continuous flat plate. Krishan and Rai (10) and Mishra (11) have studied theoretically temperature and velocity profiles, respectively, for transpiration between two concentric cylinders for viscous flow. Bahl (12) has studied the stability of viscous flow between concentric cylinders with transpiration. With the exception of flat plates, there is little data regarding transpiration from other geometries, particularly cylinders. Thus, the purpose of this investigation was the determination of the effect of mass transfer on the heat transfer coefficients and moment coefficients for a rotating cylinder in a finite medium.

Although the principal concern of this investigation was the effect of transpiration on heat and momentum transfer, heat transfer coefficients and moment coefficients for a rotating cylinder with no mass transfer were also determined. A significant amount of work on heat and momentum transfer without mass transfer for concentric cylinders has been done. A representative list of contributors for heat transfer between concentric cylinders includes Gazley (13), Becker and Kaye (14), Bjorklund and Kays (15), and Sharman et al. (16). A paper on moment coefficients for rotating cylinders by Bilgen and Boulos (17) summarizes the work of Taylor (18), Wendt (19), Donnelly (20), and Theodorsen and Regier (21). Finally, a great volume of work has been done on stability of flow between rotating concentric cylinders with Taylor (22) and Chandrasekhar (23) being important contributors.

II. RESEARCH OBJECTIVES

The purpose of this investigation was to study the effect of mass transfer on heat and momentum transfer from a rotating cylinder in a finite medium. Heat transfer coefficients and moment coefficients were determined for a rotating, porous cylinder by varying mass injection rates and angular velocities. The experiment consisted of rotating a porous cylinder in a tank filled with the same fluid as the injection fluid and measuring temperature differences across the cylinder wall and across the tank to determine the heat transfer coefficient. To determine the moment coefficient, the torque on the rotating cylinder was measured.

A heat balance for the cylinder and tank system includes the following terms: heat transfer due to molecular action across the tank (q_m), heat transfer due to bulk motion inside the cylinder (q_i), and heat transfer due to bulk motion at the wall of the cylinder (q_w). Although some axial heat transfer might be expected due to natural convection, it was considered to be negligible with respect to radial heat transfer. Indeed, Chandrasekhar (24) and Dropkin and Globe (25) have shown that rotation greatly reduces natural convection even when an axial temperature gradient is imposed. Of course, there was no angular heat transfer. Finally, heat transfer due to radiation was neglected because of the high absorptivity of water. [Heat transfer due to radiation is given by

$$q_r = \frac{\sigma(T_c^4 - T_w^4)}{\frac{1-\varepsilon_c}{\varepsilon_c A} + \frac{1-\varepsilon_w}{\varepsilon_w A} + \frac{1}{AF_{cw}}}, \quad (1)$$

where the system under consideration is the cylinder denoted by the subscript c and the layer of water next to the cylinder denoted by the subscript w. Clearly, the areas are the same and the view factor F_{cw} is one. For ε_w approximately equal to one,

$$q_r = \varepsilon_c A\sigma(T_c^4 - T_w^4). \quad (2)$$

But the difference between T_c and T_w is very small so q_r is negligible]. The heat transfer terms were defined as follows:

$$q_m = h^\circ A(T_c - T_t), \quad (3)$$

$$q_i = mC_p(T_i - T_{ref}), \quad (4)$$

and

$$q_w = mC_p(T_c - T_{ref}). \quad (5)$$

Clearly,

$$q_i - q_w = mC_p(T_i - T_c) \quad (6)$$

gives the heat transfer across the cylinder wall. Equating the expressions for heat transfer across the cylinder wall and heat transfer across the tank results in the defining equation for the heat transfer coefficient with mass transfer, i.e.,

$$h^\circ = mC_p(T_i - T_c)/A(T_c - T_t). \quad (7)$$

The heat transfer coefficient with no mass transfer—h—was determined by extrapolating a plot of h versus m to m = 0.

To determine the moment coefficient, the torque on the rotating cylinder was measured. From Schlichting (26), the moment coefficient was defined by the equation,

$$C_m = \frac{\tau g_c}{0.5\ \pi \rho \omega^2 R_c^4 L} \qquad (8)$$

III. EQUIPMENT

A. HEAT TRANSFER COEFFICIENTS

Basically, the heat transfer experiment consisted of rotating a porous cylinder in a tank. The heat source was the injection fluid; a refrigerated cooling bath served as the heat sink. Figure 1 shows the method of fixing the porous cylinders to a rotating shaft with collars. Two porous cylinders--1-1/2 inches I.D. by 1-31/32 inches O.D. by 5-3/4 inches long and 2-1/4 inches I.D. by 2-3/4 inches O.D. by 5-3/4 inches long--were placed concentrically around the shaft. Allen screws perpendicular to the shaft secured the bottom collar to the shaft. The top collar was screwed into tubes connected to the bottom collar compressing the porous cylinders into O-ring gaskets. Leakage between the shaft and collars was prevented by stop-cock grease. The inner cylinder was used to diffuse the flow and assure more uniform flow through the outer cylinder. Due to the problem of corrosion, the shaft was stainless steel, the porous cylinders were sintered bronze purchased from Thermet, and the collars were aluminum. The most difficult aspect of the heat transfer experiment involved the installation of the thermocouples in the porous cylinders. Because of the very small clearances, a fine, supple thermocouple wire was required. Thus, the chromel-alumel thermocouple wire chosen was 30 gauge with no waterproof coating, since a waterproof coating would stiffen the wire too much in addition to increasing the diameter significantly. To protect the wire from water and subsequent shorting, the thermocouple wire outside the shaft was placed inside a 1/16 inch O.D. stainless steel tube. Epoxy glue was used to seal the

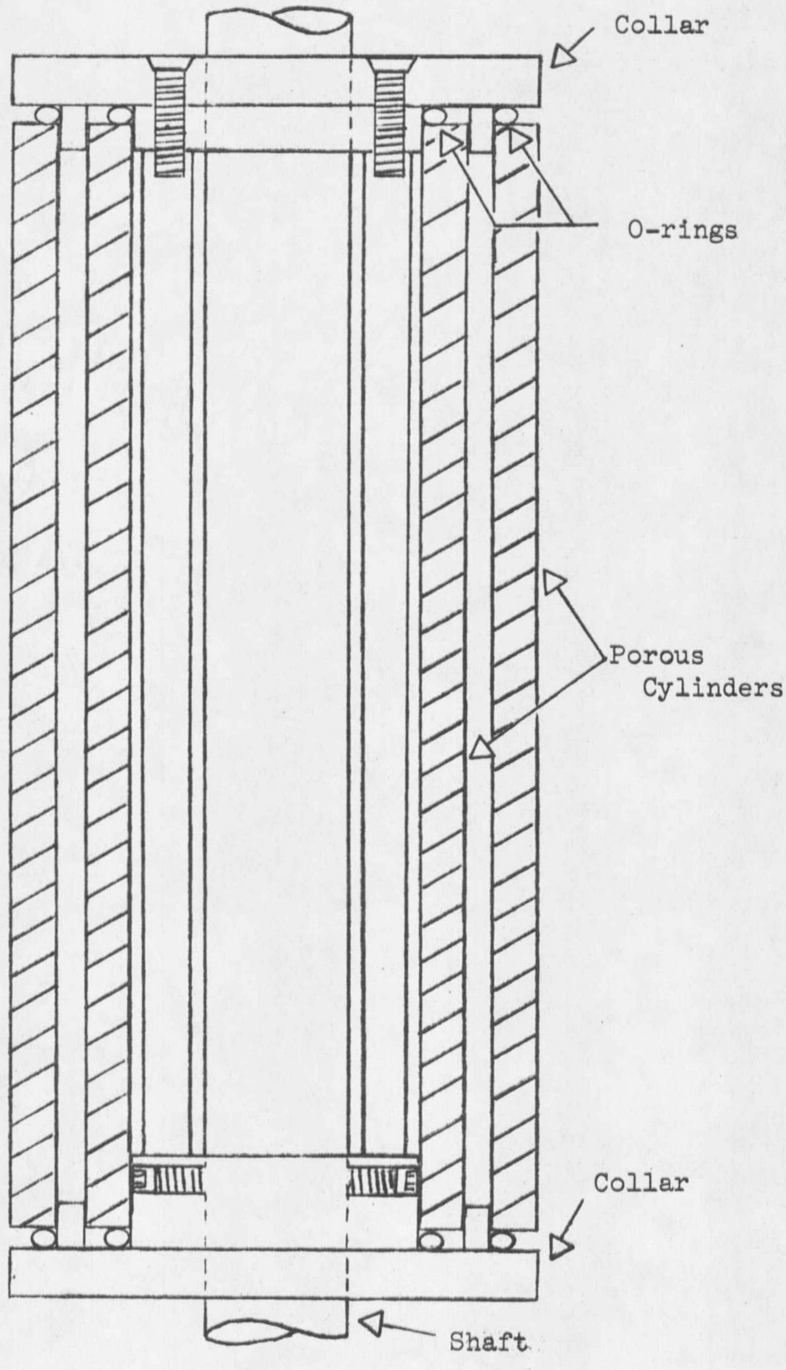

Figure 1. Porous Cylinders and Collars

thermocouple junctions to the tubes and the tubes to the shaft (see Figure 2). To transfer the emf signals from the rotating shaft a Power Instruments, Inc. model No. 6118-111-4 slip ring was used (see Figure 3). Above rotation speeds of 100 RPM there was no noise in the slip ring; occasionally below 100 RPM, a satisfactory reading could be obtained only by stopping rotation. EMF was measured on an extremely accurate potentiometer; readings could be made in millivolts to four decimals--an accuracy probably not inherent in the thermocouples.

The porous cylinder was rotated in an 11-3/4 inches diameter by 7-1/4 inches high aluminum tank with phenolic-resin board stiffening rings at top and bottom. Brass bolts were used to secure the stiffening rings. The cooling bath around the tank was made from 1/4 inch lucite and had the dimensions 16 inches by 16 inches by 10 inches high. The cooling fluid was water; overflow from the tank due to injection entered the cooling bath; an overflow weir on the cooling bath maintained constant level. The same wire was used for the tank wall thermocouple as for the cylinder thermocouples. The portion of the thermocouple wire in the cooling bath was waterproofed by slipping a length of plastic tube over it and sealing with a silicone glue at the tank wall.

The distilled water used for injection was filtered and heated and entered the shaft by means of a rotating union. Flow rates were determined using calibrated rotameters. The filter consisted of a 2 inch diameter porous plate covered by 0.8 micron filter paper. A sufficient