Table 1 Experimental thermal contact conductance values

		Integrated values[a] (W/K)	Contact conductance (W/m^2-K)
Bolted technique			
(N-m)	(in.-lb)		
0.79	7	4.19	855
1.35	12	4.83	985
1.92	17	5.58	1139
2.48	22	6.52	1331
3.04	27	7.79	1589
Bladder technique			
(kPa)	(psi)		
41.37	6	7.35	1500
62.05	9	8.92	1820
82.74	12	9.49	1937
103.42	15	9.78	1995
130.99	19	9.90	2021

[a]Least-squares curve fit integrated over 70 × 70-mm area.

dure are given in Table 1. The average contact conductance for each case can be calculated by dividing these numbers by the area of the unit cell.

As shown, the average contact conductance values for the bolted attachment technique ranged from 855 W/m^2-K for a bolt torque of 0.79 N-m to 1589 W/m^2-K for a bolt torque of 3.04 N-m. These values are slightly higher than those reported previously in the literature.[7-9] For the bladder attachment technique, the average contact conductance values ranged from 1500 W/m^2-K for a bladder pressure of 41.37 kPa to 2021 W/m^2-K for a bladder pressure of 130.99 kPa. It is important to note from Table 1 that a bladder pressure of approximately 41.37 kPa resulted in a thermal contact conductance approximately equal to that obtained for a bolt torque of 3.04 N-m.

Conclusions

This investigation compared the thermal contact conductance resulting from two different cold plate attachment techniques to determine which attachment technique could provide the highest contact conductance at the interface and the most uniform interface temperature profile. The experimental results indicate that the temperature distribution and the resulting contact conductance for the bolted attachment technique are highly nonuniform; whereas for a bladder attachment technique, the temperature and thermal contact conductance are reasonably constant. This difference is the result of the pressure distributions imposed by the two attachment techniques.

Although it is readily apparent that the bladder attachment technique results in a higher total contact conductance per unit bolt area than the bolted attachment technique, it should be noted that significant structural supports are required for the pressurized bladder system.

Acknowledgments

The authors would like to thank C. Willits of NASA Headquarters, D. Cadogan of ILC Dover, Inc., and J. McConnell of Marshall Space Flight Center for their support and advice.

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Conjugate Mixed Convection-Conduction of Micropolar Fluids on a Moving Vertical Cylinder

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Nomenclature

B = material parameter, L^2/j
C_s = specific heat of the cylinder
j = microinertia per unit mass
K_v = vortex viscosity coefficient
k = thermal conductivity of the fluid
L = length of the cylinder
Δ = material parameter, K_v/μ
γ = spin gradient
λ = material parameter, $\gamma/(j\mu)$

I. Introduction

THE problem of conjugate convection-conduction on a continuous moving cylinder has many technical applications. Well-known examples are rolling rods drawn from a die or fibers from an orifice. Among the earlier theoretical contributions, only a few papers are concerned with the conjugate problem.[1-3] The theory of micropolar fluid, formulated by Eringen[4] is expected to explain the non-Newtonian fluid flow behavior in certain fluids such as polymeric liquid, ferro liquid, and liquid with suspension. The purpose of this study is to investigate numerically the conjugate mixed convection-con-

Received Nov. 15, 1989; revision received April 17, 1990.

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duction of a micropolar fluid on a continuous moving vertical cylinder. Parametric studies of the effects of buoyancy force, property parameter, and various material parameters on the flow have been performed. Numerical results are obtained with the aid of the cubic spline collocation method.

II. Analysis

Consider an axisymmetrical cylinder of radius r_0 moving vertically with velocity U_0 from an orifice at fixed temperature T_0 in a quiescent micropolar fluid with temperature T_∞. The viscous and thermal boundary-layer equations for steady, incompressible, and laminar flow are

Continuity:

$$\frac{\partial}{\partial x}(ru) + \frac{\partial}{\partial r}(rv) = 0 \tag{1}$$

Momentum:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r}\right) = (\mu + K_v)\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) + K_v\frac{1}{r}\frac{\partial}{\partial r}(rN) + \rho g\beta(T - T_\infty) \tag{2}$$

Angular momentum:

$$\rho j\left(u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial r}\right) = \gamma\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial N}{\partial r}\right) - \frac{N}{r^2}\right] - K_v\left(\frac{\partial u}{\partial r} + 2N\right) \tag{3}$$

Energy:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{4}$$

The associated boundary conditions are

$$x = 0,\ r > r_0: \quad u = v = N = 0, \quad T = T_\infty$$

$$x \geq 0,\ r = r_0: \quad u = U,\ v = 0,\ N = -\frac{1}{2}\left(\frac{\partial u}{\partial r}\right),\ T = T_s(x)$$

$$x > 0,\ r \to \infty: \quad u \to 0,\ N \to 0,\ T \to T_\infty \tag{5}$$

Neglecting the diffusion effect, the conduction equation of the cylinder may be written in one-dimensional form as

$$U_0\frac{\mathrm{d}T_s}{\mathrm{d}x} = \frac{2k}{\rho_s C_s r_0}\frac{\partial T}{\partial r}\bigg|_{r=r_0} \tag{6}$$

with boundary condition

$$x = 0, \qquad T_s(x) = T_0 \tag{7}$$

Equations (1-4) and (6) can be rearranged as

$$\frac{\partial}{\partial X}(YU) + \frac{\partial}{\partial Y}(YV) = 0 \tag{8}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = (1 + \Delta)\left(\frac{1}{Y}\frac{\partial U}{\partial Y} + \frac{\partial^2 U}{\partial Y^2}\right) + \left(\frac{\partial G}{\partial Y} + \frac{G}{Y}\right)N_b\Theta \tag{9}$$

Table 1 Values of $U'(Y^*)$, $\Theta'(Y^*)$, and $G(Y^*)$ for $Pr = 10.0$ and $Y^* = 0.5$ at $X = 1.0$.

Δ	λ	P_c	N_b	$-U'$	$-\Theta'$	G
0.5	0.5	0.10	1.0	0.9576	0.3606	0.4788
0.5	0.5	0.10	5.0	0.5450	0.3688	0.1725
5.0	0.5	0.05	1.0	0.8907	0.7406	0.4453
5.0	0.5	0.10	1.0	0.9074	0.3578	0.4537
5.0	0.5	0.15	1.0	0.9167	0.2029	0.4583
5.0	0.5	0.10	5.0	0.7584	0.3614	0.3792
5.0	2.0	0.10	1.0	0.8245	0.3585	0.4122
5.0	2.0	0.10	5.0	0.6926	0.3615	0.3463
10.0	0.5	0.10	1.0	0.8457	0.3594	0.4229
10.0	0.5	0.10	5.0	0.7849	0.3594	0.3924

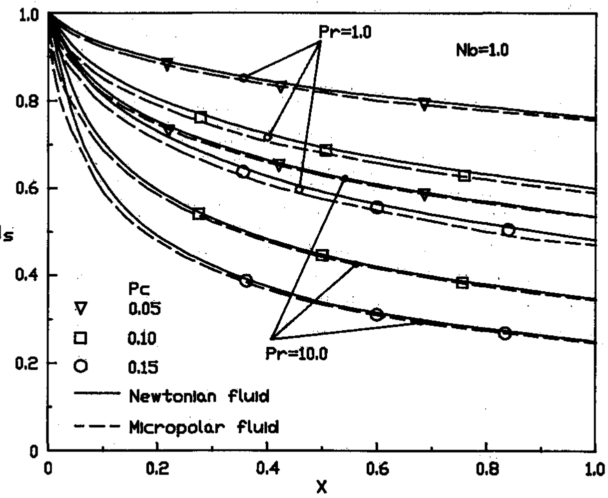

Fig. 1 Surface temperature distribution for $\Delta = 5.0$, $\lambda = 0.5$, $B = 0.1$, $Y^* = 0.5$, and $Re = 10^5$.

$$U\frac{\partial G}{\partial X} + V\frac{\partial G}{\partial Y} = \lambda\left(\frac{\partial^2 G}{\partial Y^2} + \frac{1}{Y}\frac{\partial G}{\partial Y} - \frac{G}{Y^2}\right) - \frac{\Delta B}{Re}\left(\frac{\partial U}{\partial Y} + 2G\right) \tag{10}$$

$$U\frac{\partial\Theta}{\partial X} + V\frac{\partial\Theta}{\partial Y} = \frac{1}{Pr}\left(\frac{\partial^2\Theta}{\partial Y^2} + \frac{1}{Y}\frac{\partial\Theta}{\partial Y}\right) \tag{11}$$

$$\frac{\mathrm{d}\Theta_s}{\mathrm{d}X} = 2\frac{P_c}{Y^*}\frac{\partial\Theta}{\partial Y}\bigg|_{Y=Y^*} \tag{12}$$

in which the dimensionless variables $X = x/L$, $Y = r\sqrt{Re}/L$, $U = u/U_0$, $V = v\sqrt{Re}/U_0$, $G = LN/(U_0\sqrt{Re})$, and $\Theta = (T - T_\infty)/(T_0 - T_\infty)$ represent dimensionless coordinates, axial and radial velocity, angular velocity, and temperature, respectively. Parameters that appear in the preceding equations are Prandtl number $Pr(= \nu/\alpha)$, Reynolds number $Re(= U_0L/\nu)$, buoyancy parameter $N_b(= Gr/Re^2)$, and property parameter P_c $(= k/\rho_s C_s \nu)$.

The corresponding boundary conditions of Eqs. (5) and (7) become

$$X = 0,\ Y > Y^*: \quad U = V = G = \Theta = 0$$

$$X \geq 0,\ Y = Y^*: \quad U = 1,\ V = 0,\ G = \frac{1}{2}\frac{\partial U}{\partial Y},\ \Theta = \Theta_s(X)$$

$$X > 0,\ Y \to \infty: \quad U \to 0,\ G \to 0,\ \Theta \to 0$$

$$X = 0,\ \Theta_s = 1 \tag{13}$$

where $Y^* = r_0\sqrt{Re}/L$.

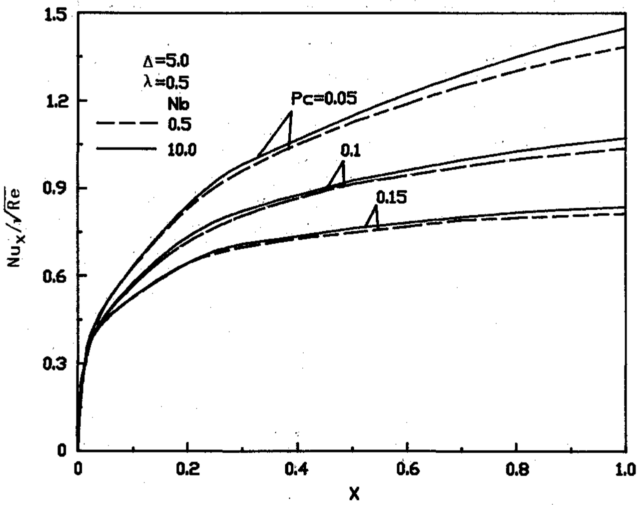

Fig. 2 Local Nusselt number for Pr = 10.0, B = 0.1, Y^* = 0.5, and Re = 10^5.

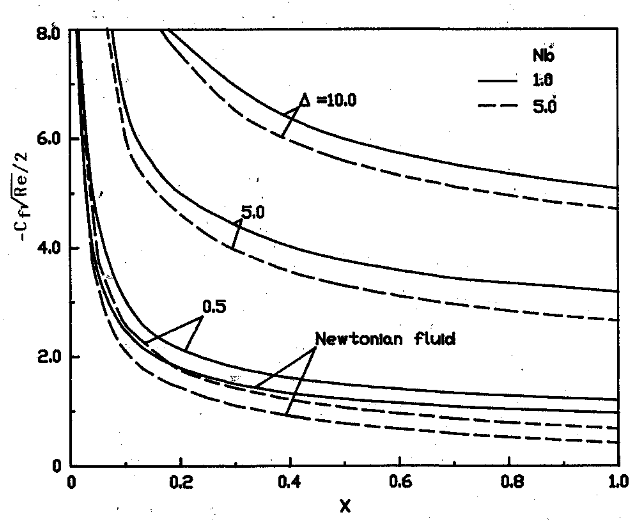

Fig. 3 Skin-friction coefficient distribution for Pr = 10.0, P_c = 0.1, λ = 0.5, Y^* = 0.5, and Re = 10^5.

The skin-friction coefficient is defined as

$$C_f = \frac{2\tau_w}{\rho U_0^2} = \frac{2}{\sqrt{Re}}\left(1 + \frac{\Delta}{2}\right)\frac{\partial U}{\partial Y}\bigg|_{Y=Y^*} \tag{14}$$

and the local Nusselt number is given by

$$Nu_x = \frac{hx}{k} = -\sqrt{Re}\,\frac{X}{\Theta_s}\frac{\partial\Theta}{\partial Y}\bigg|_{Y=Y^*} \tag{15}$$

III. Numerical Procedure

Equations (8-12) with (13) were solved with the aide of the cubic spline collocation method.[5] The problem is computed according to the following steps.

1) Determine false time step.
2) Solve Eq. (12) with guessed surface temperature.
3) Solve Eq. (11) with computed results from step 2.
4) Solve Eqs. (8-10).
5) Repeat steps 3 and 4 until the residual error is satisfied,

$$\left|\frac{\Phi_{ij}^s - \Phi_{ij}^{s-1}}{\Phi_{\max}^s}\right| < 10^{-4} \tag{16}$$

where Φ refers to U, V, G, or Θ and s denotes iteration number.

6) Return to step 2) and proceed with the calculation for the next false time step. The iteration process is continued until the convergence criterion

$$\left|\frac{Nu_x^z - Nu_x^{z-1}}{Nu_x^z}\right| < 10^{-3} \tag{17}$$

is achieved. Here z denotes the number of false time steps.

IV. Results and Discussion

The numerical results are presented in graphical and tabular form. Figure 1 shows the surface temperature distribution for various parameters. The surface temperature along the X direction decreases more rapidly for a larger value of P_c. For a given fluid, a decrease in the thermal capacity $\rho_s C_s$ implies more loss of energy to the fluid. Thus, the cylinder cools more rapidly with increasing X for a larger value of P_c. It is observed in Fig. 2 that an increase in N_b results in an increase in Nu_x, as was found in Ref. 6. This is because the buoyancy force enhances the heat transfer rate on the surface. In addition, the local Nusselt number increases more rapidly for a smaller value of P_c. Figure 3 indicates the variation of skin-friction coefficient with X distance. An increase in the vortex viscosity Δ is seen to cause an increase in C_f. Furthermore, the skin-friction coefficient of micropolar fluid is higher than that of Newtonian fluid.

Some characteristic results such as velocity and temperature gradients and angular velocity on the surface are presented in Table 1. The velocity gradient U' is seen to decrease as the value of λ increases.

V. Conclusions

Conjugating mixed convection-conduction of an incompressible micropolar fluid along a continuous moving vertical cylinder has been studied numerically. It is found that the micropolar fluid has significantly different flow and heat transfer characteristics in comparison with those of classical Newtonian fluids. The corresponding material parameters have dominant influence on the skin-friction coefficient and heat transfer rate. The effects of buoyancy parameter on the flow and thermal field have also been described.

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