Heat and Mass Transfer Coefficients for Porous Horizontal Cylinders

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INTRODUCTION

Recent models of solid fuel combustion have utilized heat transfer correlations to model the heat and mass transfer from a single particle in the heated convective flow typical of a stoker-type furnace (cf. Smith and Smoot, 1980). Typical correlations used are taken directly from heat transfer texts such as Kreith (1973) or from previous correlations developed for liquid droplets in convective flow (Ranz and Marshall, 1952).

The objective of this work was to measure heat and mass transfer coefficients for solid particles emitting vapor and compare the results with those obtainable from heat transfer-only correlations and their mass transfer analogues to determine the accuracy of applying these "textbook" correlations. The experiments were designed to provide local values of Nusselt and Sherwood numbers as a function of free stream Reynolds number for a variety of particle surface temperatures and mass transfer rates. These results were compared to those of Eckert and Soehngen (1952), which give local values of Nusselt number for cylinders in crossflow. A mass transfer analogy is used to acquire Sherwood numbers from Eckert and Soehngen's correlation, and this value is compared with the experimentally measured Sherwood number.

EXPERIMENT

The model "particle" chosen was a sintered stainless steel cylinder 7.94 cm long and 1 cm in dia. The cylinder was suspended by stainless steel tubes in a wind tunnel. The tubes allowed metered amounts of propane to be supplied to the cylinder and subsequently be emitted uniformly over the surface of the cylinder at velocities ranging from 0.072 to 0.105 cm/s. The wind tunnel supplied a steady controllable flow of heated air, with Reynolds numbers based on cylinder diameters from 150 to 700 and free stream temperatures from 65 to 200°C. These conditions were chosen as typical of ambient conditions evident to a fuel particle when first introduced to a furnace-type flow field.

The temperature and concentration profiles adjacent to the cylinder were measured using holographic interferometry (Vest, 1979) and fine-wire thermocouple measurements. Details of the experimental arrangement and calibrations are given by Nomura (1983).

In all the cases studied, the response time of the cylinder to the free stream temperature was considerably longer than the time for the boundary layer around the cylinder to form. Consequently, this experiment is treated as a quasisteady problem, with the surface temperature of the cylinder providing a slowly varying boundary condition.

The local concentration of one element of a binary ideal gas mixture can be found from the interference pattern using a form of the Lorentz-Lorentz equation from Born and Wolf (1980). In this application the appropriate form is

$$C_1 = \frac{2}{3}\frac{RNT\lambda}{LP(A_1 - A_2)} - \frac{A_2}{A_1 - A_2}\left[1 - \frac{T}{T_o}\right] \tag{1}$$

For a given binary mixture at constant pressure and a fixed wavelength of laser light, Eq. 1 gives the local concentration of component 1 as a function of fringe number N and local temperature T. The fringe numbers N are integers obtained by counting interference fringes, beginning with zero at the free stream conditions. The raw data obtained from the interferograms are thus a set of fringe numbers and their respective azimuthal and radial locations. These data are corrected for edge effects and refractions as suggested by Hauf and Grigull (1970). With the use of Eq. 1, the local concentration of a compound of a binary mixture can be calculated for each fringe number and location, if the local temperature is known at that location. The local temperature T is provided by a nonlinear least-square fit to the thermocouple data. The resulting concentration profiles were fit with third-order polynomials, using the method of least squares, to estimate the surface gradient. Finally, Nusselt and Sherwood numbers were calculated using

$$Nu_\theta = \frac{A(\partial T/\partial r)_{w,\theta}}{P_w(T_w - T_o)} \tag{2}$$

and

$$Sh_\theta = \frac{A(\partial C/\partial r)_{w,\theta}}{P_w(C_w - C_o)} \tag{3}$$

The gradients were evaluated at the cylinder surface, at a specified azimuthal location. In the results to be described, a location 90° from the upstream stagnation point was used. The area for conduction into the fluid, A, is $\pi D^2/4$, where D is the cylinder diameter. The wetted perimeter for convective heat transfer is somewhat larger than πD, due to the rough surface of the cylinder. While the free stream Reynolds numbers used were too low to support transition to turbulence even on a rough surface, the surface roughness will increase the convective heat transfer area. An effective diameter was calculated based on the mean cylinder diameter D and the known granule size of the sintered metal. This corrected value was used throughout these calculations for evaluating the perimeter, P_w.

RESULTS

The measured Nusselt numbers as a function of free stream Reynolds number are shown in Figure 1. These values use data for conditions of combined heat and mass transfer from the cylinder. The measured local Nusselt numbers at 90° from the forward stagnation point are compared with those calculated from the results of Eckert and Soehngen (1952) for smooth circular cylinders, at 90° from the stagnation point, but without mass transfer. The 90° location was chosen as the site at which the largest effect of combined heat and mass transfer will be seen, as surface blowing will alter the point of separation. An error analysis was performed, indicating that the experimental most probable error for the

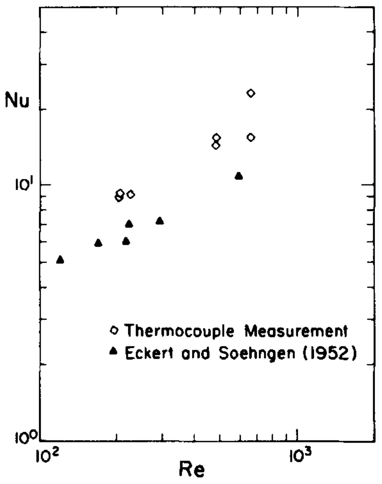

Figure 1. Comparison of Nusselt number measured (◇) with calculated value from Eckert and Soehngen (1952) (▲) at 90° from stagnation point of cylinder.

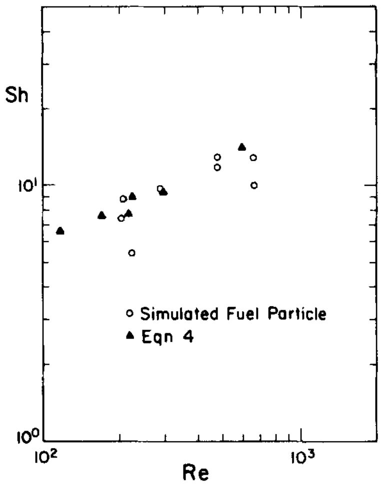

Figure 2. Comparison of Sherwood number measured (○) with calculated value using mass transfer analogy, Eq. 4 (▲), at 90° from stagnation point of cylinder.

measured Nusselt numbers was about 18%. The measured Sherwood numbers had a most probable error of 13%.

Figure 1 compares the Nusselt numbers measured in this work with those calculated from Eckert and Soehngen for bluff bodies with no mass transfer. The measured values are approximately 44% higher than those calculated from the heat transfer-only calculations, indicating enhanced heat transfer, for the range of mass transfer rates and blowing velocities tested.

The measured Sherwood number as a function of free stream Reynolds number is given in Figure 2. These data are compared with calculations based on a mass transfer analogy, using the heat transfer result of Eckert and Soehngen (1952). The analogy proposes

$$Sh = Nu \left(\frac{Sc}{Pr}\right)^{1/3} \tag{4}$$

which is considered valid for moderate mass transfer and small amounts of surface blowing (Eckert and Drake, 1972). The agreement between the measured and predicted results is good. Since these results are for a variety of surface temperature values, the agreement suggests the independence of Sherwood number with respect to surface temperature. The mass transfer analogy, Eq. 4, in fact guarantees this independence.

CONCLUSIONS

A series of experiments has been performed on a simulated solid fuel particle to measure local heat and mass transfer coefficients under conditions of combined heat and mass transfer. Under conditions for which the Soret and Dufour effects may be neglected, the major effect of mass transfer is to alter the flow field in the form of surface blowing. This effect is most evident near the point of separation, which, for a cylinder, is about 80° from the forward stagnation point. Consequently, local transfer rates near this point—at 90° from the forward stagnation point—were measured and compared to results from correlations for heat and mass transfer only. The heat transfer, or Nusselt number, experimental results showed augmented heat transfer coefficients, compared to the correlations for heat transfer without mass transfer. The measured mass transfer coefficient, or Sherwood number, showed good agreement with predictions based on a mass transfer analogy.

In the study of anisotropic solid fuels, such as wood, local heat and mass transfer coefficients are valuable due to the azimuthal variation in surface parameters. Work is continuing in this area to measure these coefficients at locations other than 90° from the forward stagnation point.

This series of experiments suggests that bluff body heat transfer correlations will have to be altered in order to predict correctly local heat transfer coefficients under conditions of combined heat and mass transfer. Mass transfer correlations appear to be adequate to predict mass transfer coefficients for the range of variables tested.

NOTATION

A	= molar refractivity, m^3/mol
C	= molar concentration, mol/mol mixture
C_p	= specific heat at constant pressure, J/kg·K
D	= diameter of cylinder, m
D_c	= molar diffusivity, m^2/s
h	= heat transfer coefficient, $W/m^2 \cdot K$
h_c	= mass transfer coefficient, $mol/m^2 \cdot mol \cdot s$
k	= thermal conductivity, W/m·K
L	= length of cylinder, m
N	= fringe number
Nu	= Nusselt number, hD/k
P	= pressure, Pa
P_w	= wetted perimeter for convective heat transfer, cm^2
Pr	= Prandtl number, $\mu C_p/K$
T	= temperature, °C
T_o	= free stream temperature, °C
Sc	= Schmidt number, ν/D_c
Sh	= Sherwood number, h_cD/D_c
ν	= kinematic viscosity, m^2/s
μ	= dynamic viscosity, kg/m·s
θ	= azimuthal coordinate
λ	= wavelength of light, nm

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