Heat Transfer to Decomposing Nitrogen Dioxide in a Turbulent Boundary Layer

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Heat transfer coefficients were measured for the dissociating system 2 $NO_2 \rightleftarrows 2NO + O_2$ in turbulent flow. Heat transfer rates to this reacting gas are limited by the kinetics of the decomposition and recombination reactions. Experimental results agree to within 10% with a film-theory solution for heat transfer accompanied by a nonequilibrium chemical reaction.

The rate of heat transfer from a solid surface to a gas mixture can be greatly augmented if the components in the gas phase undergo a reversible homogeneous chemical reaction. The temperature gradient through the boundary layer gives rise to a gradient in the equilibrium gas composition that produces an enthalpy flux owing to the counterdiffusion of reactant and product species. This flux of chemical enthalpy transported by the diffusing reaction partners may considerably enhance the rate of convective heat transport at the solid surface, especially if the enthalpy change for the chemical reaction is large. This phenomenon has been studied by a number of investigators in recent years. Most attention has been focused on the effect of air dissociation upon heat transfer to reentering space vehicles (*1, 17, 25, 28, 29*) and on the high coefficients obtained for heat transfer to dissociating nitrogen tetroxide (*10, 21, 24, 30, 32, 35, 38*).

The nitrogen tetroxide system is an example of an "equilibrium" system, in which the chemical reaction rate is so fast that the temperature and composition profiles through the boundary layer correspond essentially to local chemical equilibrium. In this case, the heat transfer rate can be predicted from standard relationships for nonreacting systems, except that effective "equilibrium" values for the heat capacity and the thermal conductivity of the gas mixture are used (*10, 21, 24, 30*). These effective equilibrium thermal properties can be much greater than the "frozen" properties that the systems would have if the chemical reaction did not take place, and the equilibrium properties generally vary with temperature more sharply than the thermal properties of nonreacting gases.

In contrast to the equilibrium case, a "frozen" system is one in which the chemical kinetic rates are slow relative to diffusion rates through the boundary layer. In this case the reaction cannot support appreciable concentration gradients, and the heat transfer process is not augmented by an enthalpy flux. Such a system was studied by Srivastava, Barua, and Chakraborti (*36*) when they measured the thermal conductivity of nitrogen dioxide–nitric oxide–oxygen mixtures at low temperatures.

Intermediate between the frozen and equilibrium systems is the case of a reaction whose kinetics are too slow to allow the attainment of local chemical equilibrium but are sufficiently fast to cause an appreciable increase in the heat transfer rate. In such nonequilibrium systems the heat transfer rate is strongly affected by the homogeneous chemical reaction rate. The use of effective thermal properties is not a fruitful approach in this case, because the effective properties vary with the boundary layer thickness as well as the chemical kinetic rate. Theoretical studies of the effects of finite chemical reaction rates have been reported by several investigators (*4* to *9, 16, 17*), but no experimental studies have been reported. The only published heat transfer data which appear to show chemical kinetic effects are data on the thermal conductivity of dissociating nitrogen tetroxide reported by Coffin and O'Neil (*11*). These data showed deviations from equilibrium theory at low pressures. Brokaw (*9*) discussed these deviations in terms of his nonequilibrium theory for thermal conductivity. However, a lack of knowledge about the kinetics of nitrogen tetroxide dissociation prevented a quantitative comparison of theory and experiment in this case.

There have been no experimental results published for the important case of heat transfer to a nonequilibrium system in turbulent flow. Thus this work was undertaken with the objective of obtaining data on the rate of heat transfer from a solid wall to a nonequilibrium reacting gas in turbulent flow. Decomposing nitrogen dioxide was chosen as the chemical system because the chemical kinetic rate has been studied in considerable detail. The turbulent boundary layer on a rotating cylinder was chosen as the fluid mechanical system because of its one-dimensional nature and its relative experimental simplicity.

THEORY

The theoretical background for this study has been presented previously, and only a brief account of it will be given here. Employing a film-theory model and linearizing the problem for small values of the temperature driving force, Brian and Reid (*6*) obtained the relation

$$\phi = \frac{\dfrac{\sqrt{m\eta}}{\tanh\sqrt{m\eta}}}{1 + \dfrac{1}{\eta}\left[\dfrac{\sqrt{m\eta}}{\tanh\sqrt{m\eta}} - 1\right]} \tag{1}$$

The variable ϕ is the ratio of the heat transfer coefficient for a chemically reacting system to the coefficient which would be expected if the reaction did not take place. The quantity $\sqrt{m}$ is interpreted as the ratio of the chemical reaction rate to the diffusional rate in the boundary layer.

The parameter η is the ratio of the equilibrium effective thermal conductivity to the frozen conductivity, and it represents the maximum factor by which the chemical reaction may increase the heat transfer coefficient. For a frozen system, m equals zero, and ϕ is equal to unity; in this case the chemical reaction does not influence the heat transfer rate. In an equilibrium system, m approaches infinity and ϕ becomes equal to η. In the linearized theory (*6*) m and η are expressed in terms of partial derivatives of an unspecified reaction kinetic expression; thus the solution is quite general in regard to the chemical system. However, the solution is valid only for small values of the temperature driving force. Furthermore, the validity of the film-theory model is open to question.

Subsequently, Brian (*5*) presented linearized solutions for an eddy diffusion model of turbulent flow in a pipe, using Deissler's (*13*) eddy diffusivity function. These results showed the effects of Reynolds, Prandtl, and Schmidt numbers on the solution. It was found that, when the Lewis number is equal to unity, the results are quite insensitive to wide variations in the Reynolds and Prandtl numbers and are well approximated by Equation (1). Thus it appears that the film-theory model should be quite useful for systems with Lewis numbers near unity. However, the eddy diffusion model cannot be justified rigorously, and Brian's analysis employed time-mean temperature and concentration values in the reaction kinetic expression, thus neglecting effects of temperature and concentration fluctuations on the reaction rate. Therefore, an experimental confrontation of the conclusions from this study is clearly desirable.

To assess the effect of a large temperature driving force, Brian and Bodman (*7*) obtained film-theory solutions for heat transfer accompanied by a reaction analogous to the nitrogen dioxide decomposition reaction. They employed the known kinetic expression for this system, which is second-order forward, third-order reverse, with the forward rate constant being an Arrhenius type of temperature function. They found that their results were well approximated by Equation (1) when the temperature driving force was less than 40°F., but deviations became substantial at higher driving forces. However, they modified Equation (1) by substituting ϕ_∞ for η and $\tilde{m}$ for m to obtain

$$\phi_\lambda = \frac{\dfrac{\sqrt{\phi_\infty \tilde{m}}}{\tanh \sqrt{\phi_\infty \tilde{m}}}}{1 + \dfrac{1}{\phi_\infty}\left[\dfrac{\sqrt{\phi_\infty \tilde{m}}}{\tanh \sqrt{\phi_\infty \tilde{m}}} - 1\right]} \qquad (2)$$

and this modified expression approximated all their results to within 3.7%. The parameter ϕ_∞ is the solution for an infinitely rapid chemical reaction obtained for finite values of λ, the dimensionless temperature driving force; it is calculated from Equations (20) and (21) in reference 7. The variable $\tilde{m}$ differs from m only in that the forward reaction rate constant is evaluated at a temperature equal to $(0.45\ T_w + 0.55\ T_o)$ instead of at T_o. Over the range of variables covered in the present study, Equation (2) approximates the film-theory analytical results of Brian and Bodman to within 1%.

Since the frozen Lewis number for the nitrogen dioxide–nitric oxide–oxygen system varies from 0.9 to 1.1 for the conditions of interest in the present study, it will be assumed that the film-theory model should be a good approximation. Hence Equation (2) will be used to provide theoretical predictions for comparison with the experimental results obtained in this study.

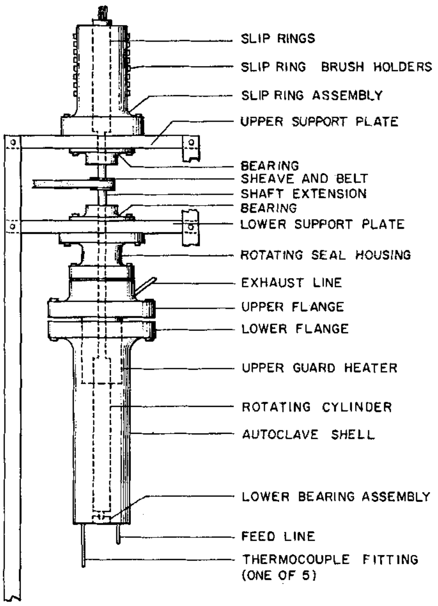

Fig. 1. Schematic drawing of the rotating cylinder heat transfer apparatus.

EXPERIMENTAL

The experimental apparatus, shown schematically in Figure 1, consisted of a stainless steel autoclave, 4 in. in diameter and 18 in. long, equipped with an axially mounted, rotating stainless steel cylinder with an O.D. of 1.65 in. A tubular heating element having a capacity of 2,200 w. was sealed within the rotating cylinder. The surface temperature of the cylinder was measured by five thermocouples fitted in the annulus between the tubular heater and the pipe which makes up the cylinder. The electrical leads from the heater and the thermocouples were passed up through the center of the hollow shaft extension. Electrical connections to these leads were achieved by a slip-ring assembly mounted at the top of the apparatus. Temperatures in the gas phase were measured by five thermocouples inserted through fittings in the bottom plate of the autoclave. These thermocouples were arranged at various heights and radial positions in the annular gas phase between the rotating cylinder and the autoclave wall. The temperatures at several positions on the autoclave wall were also measured.

The cylinder was rotated by a 1/3 h.p. electric motor. A rotating seal was provided so that pressures as high as 450 lb./sq. in. could be maintained in the autoclave, while rotational speeds were varied from 100 to 1,500 rev./min.

Radiative heat transfer was minimized by lining the inner wall of the autoclave with gold foil and by coating the outside surface of the rotating cylinder with a thin film of gold. The gold film on the rotating cylinder degenerated during the course of the experimental program, necessitating frequent radiation calibration experiments. The thermocouples in the gas phase were equipped with gold foil radiation shields which allowed an accurate determination of the temperature in the turbulent gas mixture.

Very little instrumentation was required to obtain the necessary experimental data. The power input to the rotating cylinder was measured by a wattmeter. The rotational speed of the cylinder was monitored by a small d.c. generator mounted on the shaft of the electric motor. Accurate Bourdon type of gauges were used to measure the pressure in the autoclave, and, as discussed earlier, thermocouples were used to measure the temperatures of the rotating cylinder surface, the autoclave wall, and the bulk gas.

The rotating cylinder heat transfer apparatus was first operated with nitrogen as the heat transfer medium in order to establish a correlation for heat transfer in a nonreacting

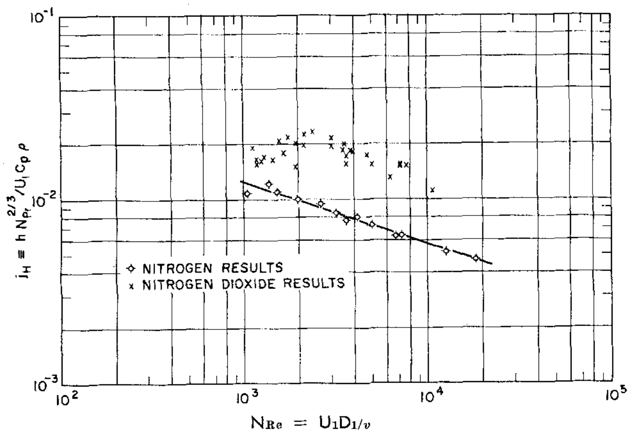

Fig. 2. Heat transfer j_H factors for nitrogen and nitrogen dioxide experiments.

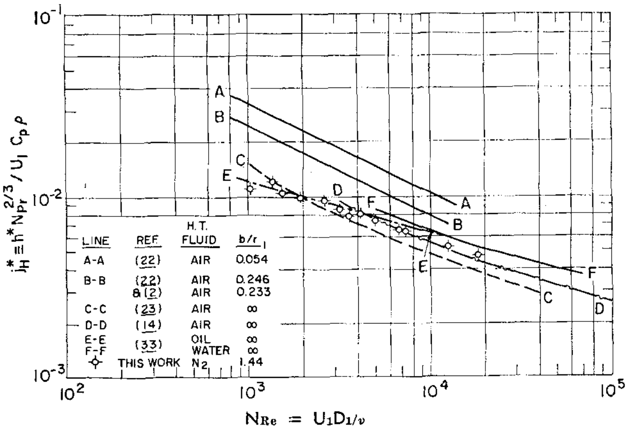

Fig. 3. Heat transfer correlation for rotating cylinder equipment with nonreacting heat transfer media.

gas. The nitrogen experiments were carried out for wide ranges of temperature, pressure, and rotational speed. The information gathered in these experiments served as a reference for evaluating the data for heat transfer in a chemically reacting gas. Moreover, these are the only experiments ever performed which measured heat transfer rates in rotating cylinder equipment having a wide annular gap.

The rate of heat transfer from the surface of the rotating cylinder to decomposing nitrogen dioxide was measured for rotational speeds between 320 and 1,090 rev./min. The gas temperature was varied from 830° to 1,012°F., while pressures between 2 and 11 atm. were investigated. The heat transfer coefficients for these, as well as the nitrogen experiments, were computed by dividing the convective heat flux at the cylinder surface by the temperature driving force between the cylinder and the gas.

In computing the convective heat flux for each experiment, corrections for axial conduction and for radiation were subtracted from the measured total heat flux. The former correction was computed from the axial temperature profile in the cylinder. The latter correction was computed from the measured temperatures of the cylinder, the gas, and the autoclave wall, plus the measured emissivities of the cylinder and autoclave surfaces and the absorptivity of the gas as given in references *18, 20, 26,* and *27.* In order to evaluate the emissivity of the cylinder surface and its changes as the gold film deteriorated, frequent radiation calibration tests were performed throughout the course of this investigation. These calibration runs were made at high temperatures with nitrogen gas and with no rotation. Furthermore, the nitrogen heat transfer experiments were not all made at the beginning of the experimental program, but they were interdispersed throughout the course of this investigation in order to serve as a check on the accuracy of the radiation correction.

A more detailed description of the experiments and the results is given in reference *4,* and summary tables of experimental data are included in the Appendix.*

RESULTS AND DISCUSSION

The experimental results are plotted in Figure 2 as heat transfer j_H factor vs. Reynolds number. Consider first the results for heat transfer to nitrogen gas. The precision of these data is quite good, especially in light of the wide range of experimental conditions encountered. For example, the emissivity of the rotating surface varied from 0.10 to 0.73 during the course of these experiments. In addition, the data were obtained at pressures which varied from 2 to 9 atm., at gas temperatures between 400° and 1,000°F., and at wall temperatures between 630° and 1,150°F.

For Reynolds numbers greater than 1,500, the maximum deviation of experimental points from the best line drawn through the data is 6%. For Reynolds numbers below 1,500 the deviation increases to a maximum of 13%. This type of behavior was anticipated, since the axial conduction and radiation corrections become large percentages of the total heat flux for the experiments at low Reynolds number, thus increasing the experimental error.

In Figure 3 it can be seen that the present results with nitrogen gas are in good agreement with the results of previous investigations of heat transfer to nonreacting fluids. Of particular interest is the fact that only very small differences are noted between the present data and data from experiments with heated cylinders rotating in large fluid volumes ($b/r_1 = \infty$). That a negative one-third slope is found in the j_H^* factor correlation for the present data is in excellent agreement with the results of studies for infinite b/r_1 values. This slope is in marked contrast to the data of Kays and Bjorklund (*22*) and of Becker (*2*); these investigators found a negative one-half exponent on the Reynolds number for equipment having low b/r_1 values (curves *A-A* and *B-B* in Figure 3).

Figure 3 shows remarkable correlation in that it brings together data for experiments using water, oil, and nitrogen heat transfer media in equipment having various b/r_1 values. Because of the high precision of the data obtained in this study and the consistency of all the sets of data in Figure 3, it is estimated that the j_H^* correlation for the present experimental apparatus is accurate to about 5%.

Figure 4 provides yet another basis for evaluating the nonreacting heat transfer coefficients measured in this investigation. In this figure the values of j_H^* determined in the nitrogen experiments are compared with mass transfer and friction factor data as measured by previous investigators. All the data shown in this figure were obtained in experiments with equipment having large b/r_1 values. The agreement between the j_H^* values obtained in this study and the j_D and $f/2$ values established in previous studies lends further confidence to the present experimental technique and methods of data reduction.

Effect of Chemical Reaction

Returning to Figure 2, the j_H factors for heat transfer to decomposing nitrogen dioxide can be compared with those for nitrogen. For the nitrogen dioxide runs, the j_H factor was computed using "frozen" values of the thermal conductivity and the heat capacity of the nitrogen dioxide–nitric oxide–oxygen gas mixture of a composition corresponding to chemical equilibrium at the bulk gas temperature. These properties, together with the viscosity

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* Tabular material has been deposited as document 8465 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or 35-mm. microfilm.

and diffusivity for the gas mixture, were computed from published property values for nitric oxide and oxygen and from values for nitrogen dioxide which were estimated by the methods of reference *19*. The Lennard-Jones constants for nitrogen dioxide which were used in these calculations were those suggested by Srivastava, Barua, and Chakraborti (*36*): $\epsilon/k = 355°$K. and $\sigma = 3.09$ Å. The details of the calculations and the results are reported elsewhere (*4*).

It is seen from Figure 2 that the heat transfer rates in the nitrogen dioxide system are greater than those in nitrogen; furthermore, the data at any specified Reynolds number are considerably more scattered in the case of nitrogen dioxide. Both of these observations indicate that the heat transfer rate is increased by the presence of a chemical reaction.

Experimental values of ϕ are readily determined by using Figure 2. The value of ϕ for a nitrogen dioxide experiment is equal to the ratio of j_H for that experiment to the value of $j_H{}^*$ as read at the same Reynolds number from the best line through the nitrogen data. The values of m, η, ξ_o, and λ were computed for each experimental point by using $j_H{}^*$; the equilibrium constant, forward rate constant, and activation energy for nitrogen dioxide decomposition; and the frozen thermal properties and diffusivity for the gas mixture. The equilibrium constant was obtained from reference *3*, and the forward rate constant and activation energy were obtained from reference *31*.

Figure 5 presents the results of the nitrogen dioxide heat transfer experiments as ϕ plotted vs. $\sqrt{m}$ for various values of η, λ, and ξ_o. The lines shown on this figure were computed from Equation (2), assuming a λ value of 2 and a ξ_o value of 0.5. However, the value of λ varied between 1.08 and 2.63 and the value of ξ_o ranged between 0.41 and 0.70 for the experimental points shown in Figure 5. Since the experimental data only approximately correspond to the values of λ and ξ_o used in computing values of ϕ_λ, the comparison between the points and lines can be made only approximately.

The experimental values of ϕ shown in Figure 5 are considerably smaller than the values predicted by equilibrium theory, which are indicated by the asymptotic values of ϕ at large values of $\sqrt{m}$. Clearly, as theoretically predicted, the kinetics of the decomposition and recombination reactions are too slow to produce local chemical equilibrium in the turbulent boundary layer. Moreover, Figure 5 indicates that the parameter $\sqrt{m}$ does an acceptable job of correlating the heat transfer data as the experimental values of ϕ generally increase with increasing $\sqrt{m}$ at a constant value of η.

Figure 5 also points up a shortcoming of this investigation, that is, the narrow range of $\sqrt{m}$ values for which data were obtained. However, the experimental points that are available correspond to conditions where the chemical kinetic rates are approximately equal to the diffusion rates in the turbulent boundary layer ($\sqrt{m} \sim 1$). Under these conditions the effect of $\sqrt{m}$ upon ϕ is maximized, and significant variations can be effected in ϕ even for the narrow range of $\sqrt{m}$ values investigated in this study.

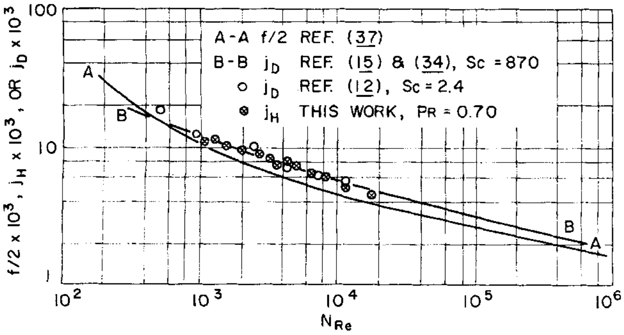

Fig. 4. Heat, mass, and momentum transfer correlation for rotating cylinder equipment.

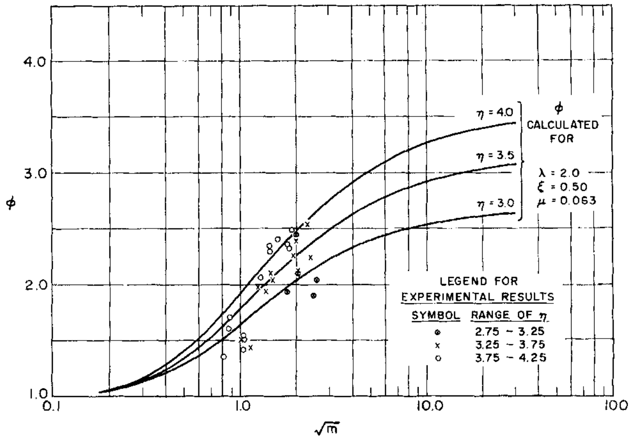

Fig. 5. Results of nitrogen dioxide experiments plotted as ϕ vs. $\sqrt{m}$.

Since the experimental ϕ values all correspond to different values of η, λ, and ξ_o, Figure 5 permits only an approximate comparison between ϕ_{EXP} and ϕ_λ. Therefore in Figure 6 ϕ_{EXP} for each experimental point is plotted vs. ϕ_λ computed from Equation (2) at the values of η, λ, and ξ_o for the experimental point in question. The agreement between experiment and theory is generally very good for all but a group of seven points whose experimental values of ϕ fall some 20 to 30% below theoretically predicted values of ϕ_λ. These seven data points were all obtained at Reynolds numbers less than 2,000. When one recalls that there was significant scatter in the nitrogen data at low Reynolds numbers, these large errors for the nitrogen dioxide tests are not surprising. Further examination of Figure 6 reveals that all but one of the remaining experi-

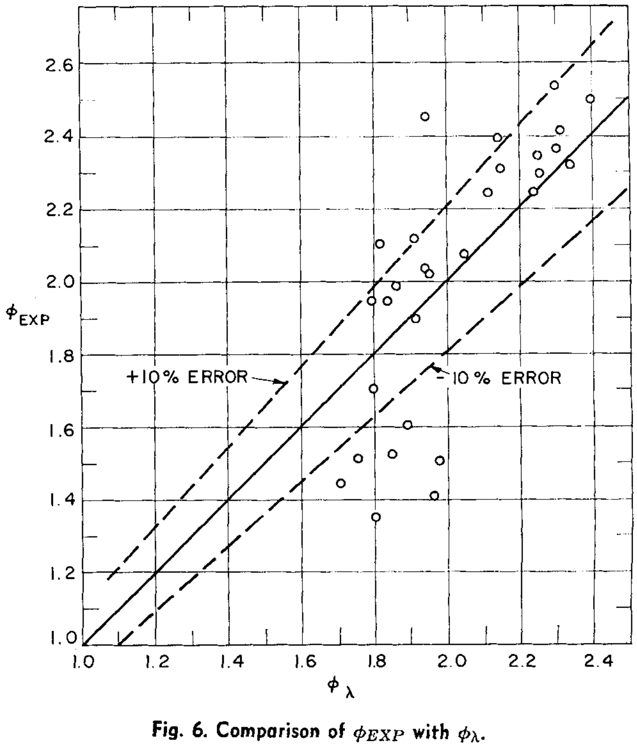

Fig. 6. Comparison of ϕ_{EXP} with ϕ_λ.

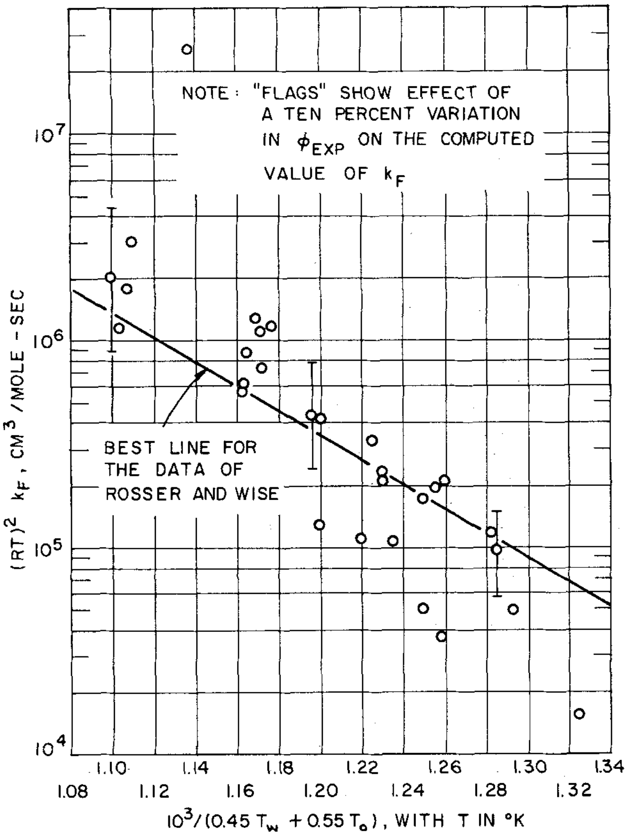

Fig. 7. Chemical kinetic constant for the decomposition of nitrogen dioxide as determined from the results of heat transfer experiments.

mental points agree very well with theoretically predicted values.

Since a great many corrections were applied to each set of raw experimental data to obtain a value of the heat transfer coefficient, it is necessary to carry out a detailed analysis to estimate the probable errors in the final experimental results. This analysis indicates that for most experiments the values of j_H^* are good to 6%, results for j_H are accurate to 8%, and results for ϕ are generally subject to errors of 10% or less. The estimated errors in the nitrogen dioxide results are slightly greater than errors in the nitrogen results because of uncertainties in predicting the frozen properties of nitrogen dioxide–nitric oxide–oxygen gas mixtures. However, the analysis also shows that errors in the heat transfer coefficient as high as 18% would be expected in results from a few experiments in which the convective heat flux is very low. These estimated errors agree very well with the observed precision in the experimental data, thus indicating that the sources of error have been properly evaluated.

Another way to present the comparison between the experimental results of this study and the film-theory prediction of Brian and Bodman (7) is to use Equation (2) to compute the reaction rate constant from the heat transfer data. Thus the right-hand side of Equation (2) is set equal to ϕ_{EXP}, and the resulting expression is solved for $\tilde{m}$. From this a value for k_F is determined and this value is plotted in an Arrhenius plot vs. the reciprocal of the average temperature ($0.45\ T_w + 0.55\ T_o$). The results of such a procedure are shown in Figure 7.

An examination of Figure 7 shows that the computed values of k_F generally agree very well with the results of Rosser and Wise (31). Very little confidence can be placed in the seven points which fall well below the other data. As mentioned previously, these seven points correspond to experiments in which the convective heat flux was very low, and thus they are subject to a high degree of uncertainty. If these data are ignored, the k_F values are found to agree well with the results of Rosser and Wise. The agreement between the experimental and literature values of the chemical rate constant over a wide range of temperature is a very strong confirmation of both the theoretical and experimental aspects of this investigation. It is also good evidence that the chemical reaction did not occur heterogeneously on the cylinder surface at an appreciable rate.

The scatter in the values of k_F in Figure 7 is considerably greater than the scatter in the values of ϕ_{EXP} from which the kinetic constants were derived. This greater scatter is due to the relatively low sensitivity of ϕ to variations in k_F. As an indication of the type of errors inherent in this type of back calculation, "flags" have been placed on some of the points in Figure 7 to show the effect of positive and negative ten percent fluctuations in ϕ_{EXP}. Figure 7 shows that a 10% error in the heat transfer measurement can shift the computed kinetic constant by as much as a factor of 2. It is thus apparent that very accurate experimental results must be obtained if reliable kinetic data are to be generated from heat transfer experiments.

The agreement between Equation (2) and the experimental results of this study, as shown in Figures 5, 6, and 7, is taken as confirmation of the utility of the film-theory model for predicting the rate of heat transfer to a reacting gas in turbulent flow, at least for systems with frozen Lewis numbers near unity.

CONCLUSIONS

Experimental data are presented for heat transfer to decomposing nitrogen dioxide in the turbulent boundary layer on the surface of a rotating cylinder. The results are found to be intermediate between those expected for an equilibrium reaction and those for a frozen reaction, and they show clearly the effect of the nitrogen dioxide decomposition kinetics upon the heat transfer rate.

The results are compared with a film-theory solution published previously. The justification for using film theory was based upon earlier work in which solutions for an eddy diffusion model were found to agree well with film-theory solutions when the Lewis number was equal to unity. Nevertheless, the eddy diffusion model cannot be justified rigorously; furthermore the effects of the turbulent temperature and composition fluctuations on the reaction rate were neglected in the eddy diffusion analysis. Thus the conclusion that the film-theory model is applicable to a turbulent system with a Lewis number near unity required experimental verification.

The experimental results were found to agree well with the film-theory predictions. This agreement confirms the utility of the film-theory model for predicting the rate of heat transfer to a nonequilibrium chemically reacting gas in turbulent flow when the frozen Lewis is near unity.

ACKNOWLEDGMENT

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NOTATION

b = width of annular gap in heat transfer apparatus
c = molar density, moles/cc.
c_p = frozen heat capacity, cal./(g.)(°K.)

D = binary diffusion coefficient, computed as the mean of the diffusivity for oxygen in nitrogen dioxide and that for nitric oxide in nitrogen dioxide, sq. cm./sec.
D_1 = diameter of rotating cylinder, cm.
E = activation energy for the decomposition of nitrogen dioxide, equal to $\mathcal{H} + 2\,RT$, cal./mole
f = friction factor, dimensionless
h = heat transfer coefficient, cal./(sec.) (sq. cm.) (°K.)
ΔH = enthalpy of reaction, cal./mole of nitrogen dioxide
$\mathcal{H}$ = activation enthalpy for the decomposition of nitrogen dioxide, equal to $E - 2RT$, cal./mole
$j_H{}^*$ = $h^*\, N_{Pr}{}^{2/3}/U_1\, \rho\, c_p$
j_H = $h\, N_{Pr}{}^{2/3}/U_1\, \rho\, c_p$
j_D = $\dfrac{k^o N_{Sc}{}^{2/3}}{U_1}$
k^o = mass transfer coefficient, cm./sec.
k = frozen thermal conductivity, cal./(sec.) (cm.) (°K.)
k_F = specific rate constant for the decomposition of nitrogen dioxide, mole/(cc.) (sec.) (atm.^{2})
m^+ = $\dfrac{k_F\, p^2\, y_o{}^2}{c_o\, D_o}\left(\dfrac{k}{h^*}\right)^2$
m = $m^+\left[\dfrac{3}{\xi_o(1-\xi_o)}\right]$
$\tilde{m}$ = modified value of m, equal to m exp $\left(\dfrac{1}{\dfrac{1}{0.45\lambda} + \mu}\right)$
N_{Le} = frozen Lewis number, equal to N_{Sc}/N_{Pr}
N_{Pr} = frozen Prandtl number, $\dfrac{c_p\, \nu\, \rho}{k}$
N_{Re} = Reynolds number, $D_1 U_1/\nu$
N_{Sc} = Schmidt number, ν/D
p = pressure, atm.
q = heat flux, cal./(sq. cm.) (sec.)
R = universal gas constant, cal./(mole) (°K.)
r_1 = radius of rotating cylinder, cm.
T = temperature, °K.
U_1 = circumferential velocity of rotating cylinder, cm./sec.
y = mole fraction of nitrogen dioxide

Greek Letters

η^+ = $1 + \dfrac{(\Delta H)^2}{RT_o{}^2}\left(\dfrac{c_o\, D_o}{k}\right)$
η = $1 + (\eta^+ - 1)\left(\dfrac{\xi_o(1-\xi_o)}{3}\right)$
λ = $\dfrac{\mathcal{H}(T_w - T_o)}{RT_o{}^2}$
μ = $\dfrac{RT_o}{\mathcal{H}}$
ν = kinematic viscosity, sq. cm./sec.
ξ = degree of conversion of decomposition reaction, equal to $(1 - y)/(1 + y/2)$
ρ = density, g./cc.
ϕ = h/h^*
ϕ_∞ = value of ϕ for an infinitely rapid chemical reaction
ϕ_λ = value of ϕ as computed from Equation (2)
ϕ_{EXP} = experimental value of ϕ

Subscripts

o = conditions in bulk gas
w = condition at the surface of the rotating cylinder

Superscripts

$*$ = property of a nonreacting gas

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