HEAT AND MASS TRANSFER IN A TURBULENT REACTING FLOW IN AN ANNULAR CHANNEL (INTERNAL HEAT CONDUCTOR). PART 1. STABILIZED HEAT-TRANSFER SEGMENT

L. V. Mishina, B. E. Tverkovkin, and L. N. Shegidevich

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Theoretical formulas are derived for the heat and mass transfer characteristics in a turbulent chemically nonequilibrium flow. The functions needed to derive the mean-mass values for the relative temperature and composition have been calculated throughout the range in the flow parameters, namely from quasifrozen to quasiequilibrium, and the same applies to the Nusselt number at the inner surface and the relative adiabatic temperature on the stabilized heat-transfer part. Fitted expressions are derived for those functions, which give the major characteristics with errors of ≤ 3%.

We consider a hydrodynamically stabilized chemically nonequilibrium flow in a channel formed by coaxial cylinders having inert impermeable surfaces and constant specific heat fluxes there (q_{c1} = const and $q_{c2} = 0$).

The reversible dissociation of nitrogen dioxide occurs homogeneously in the flow. The [1] analysis implies that the resulting gas mixture can be represented as of quasibinary type $2A \rightleftarrows 3B$.

The inlet is a flow having a uniform temperature profile T_0 and a chemically equilibrium composition $x_0 = x_e(T_0)$.

The boundary-layer approximation for the heat and mass transfer give

$$f(R)\frac{\partial\Theta}{\partial\eta}=\frac{1}{R}\frac{\partial}{\partial R}\left(Rg(R)\frac{\partial\Theta}{\partial R}\right)-\beta^2(\varkappa\Theta-Y^*);$$
$$f(R)\frac{\partial Y^*}{\partial\eta}=\frac{1}{R}\frac{\partial}{\partial R}\left(Rg(R)\frac{\partial Y^*}{\partial R}\right)+\beta^2(\varkappa\Theta-Y^*);$$
$$\Theta(R,\ 0)=0,\quad\left(\frac{\partial\Theta}{\partial R}\right)_{R_1}=-1,\quad\left(\frac{\partial\Theta}{\partial R}\right)_{R_2}=0;\tag{1}$$
$$Y^*(R,\ 0)=0,\quad\left(\frac{\partial Y^*}{\partial R}\right)_{R_1}=0,\quad\left(\frac{\partial Y^*}{\partial R}\right)_{R_2}=0.$$

Some simplifying assumptions have been made in writing (1): the properties of the flow are constant, the Lewis number $Le_f = 1$, and the ratios of the molecular and turbulent Schmidth and Prandtl numbers are $Sc_f/Sc_t = Pr_f/Pr_t$. The mass source is represented as a Taylor-series expansion in the deviations in the composition from the local equilibrium value and is linearized:

$$I_M = n^2K_dF(x);$$
$$F(x)=a_1(x_e-x)\left[1-\frac{1}{2}\frac{a_2}{a_1}(x_e-x)+\frac{1}{6}\frac{a_3}{a_1}(x_e-x)^2\right]\simeq a_1(x_e-x),\tag{2}$$

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in which

$$a_1 = -\left(\frac{\partial F}{\partial x}\right)_{x_e} \equiv 1{,}5\,\frac{(1-1{,}5x_e)(2-x_e)}{x_e};$$
$$a_2 = \left(\frac{\partial^2 F}{\partial x^2}\right)_{x_e}; \quad a_3 = \left(\frac{\partial^3 F}{\partial x^3}\right)_{x_e}.$$

The possible errors due to mass source linearization have been discussed in detail in [1, 2]; the following transformation is made:

$$(x_e - x) = (x_e - x_{0e}) - (x - x_{0e}) = \left(\frac{q_{c1}\Delta}{\lambda_f}\right)[\varkappa\Theta - Y^*]\,\frac{1}{\alpha'}. \tag{3}$$

We introduce the auxiliary functions

$$V = \Theta + Y^*, \quad W = \varkappa\Theta - Y^*. \tag{4}$$

For V(R, η) we get

$$f(R)\frac{\partial V}{\partial \eta} = \frac{1}{R}\frac{\partial}{\partial R}\left[Rg(R)\frac{\partial V}{\partial R}\right];$$
$$V(R,\ 0) = 0, \quad \left(\frac{\partial V}{\partial R}\right)_{R_1} = -1, \quad \left(\frac{\partial V}{\partial R}\right)_{R_2} = 0. \tag{5}$$

Equation (5) corresponds to the temperature distribution in turbulent flow in an annular channel having q_{c1} = const, q_{c2} = 0 for a chemically inert coolant. The solution to (5) is written as

$$V(R,\ \eta) = \Theta + Y^* \equiv \Theta_f(R,\ \eta). \tag{6}$$

The equation for W(R, η) is

$$f(R)\frac{\partial W}{\partial \eta} = \frac{1}{R}\frac{\partial}{\partial R}\left[Rg(R)\frac{\partial W}{\partial R}\right] - \gamma^2 W,$$
$$W(R,\ 0) = 0, \quad \left(\frac{\partial W}{\partial R}\right)_{R_1} = -\varkappa, \quad \left(\frac{\partial W}{\partial R}\right)_{R_2} = 0, \tag{7}$$

in which $\gamma^2 = \beta^2(1+\varkappa)$ is the thermal chemical nonequilibrium parameter. If $\gamma^2 = 0$ (chemically inert flow), $Y_f^* = 0$, $W_f = \varkappa\Theta \equiv \varkappa\Theta_f$. We introduce

$$P^*(R,\ \eta) = \frac{W}{\varkappa}. \tag{8}$$

Then (7) is rewritten as

$$f(R)\frac{\partial P^*}{\partial \eta} = \frac{1}{R}\frac{\partial}{\partial R}\left[Rg(R)\frac{\partial P^*}{\partial R}\right] - \gamma^2 P^*,$$
$$P^*(R,\ 0) = 0, \quad \left(\frac{\partial P^*}{\partial R}\right)_{R_1} = -1, \quad \left(\frac{\partial P^*}{\partial R}\right)_{R_2} = 0. \tag{9}$$

We perform an integral transformation with respect to the radial coordinte [3]:

$$\xi = \frac{1}{G}\int_{R_1}^{R}\frac{1}{\sqrt{g}}\,dR, \quad G = \int_{R_1}^{R_2}\frac{1}{\sqrt{g}}\,dR, \quad 0 \leqslant \xi \leqslant 1. \tag{10}$$

We use (10) to rewrite (9):

$$f(\xi)F(\xi)G^2\frac{\partial P}{\partial\eta}=\frac{\partial}{\partial\xi}\left[F(\xi)\frac{\partial P}{\partial\xi}\right]-\gamma_T^2PF(\xi),$$

$$P(\xi,\ 0)=0,\qquad\left(\frac{\partial P}{\partial\xi}\right)_{\xi=0}=-1,\qquad\left(\frac{\partial P}{\partial\xi}\right)_{\xi=1}=0,\tag{11}$$

in which

$$F(\xi)=R\sqrt{g};\quad P=\frac{P^*}{G}=\frac{W}{\varkappa G};\quad \gamma_T^2=(\gamma G)^2.\tag{12}$$

The new coordinate from (10) enables one to extend the wall region and thus to use a larger step in the numerical solution for large Re [3].

Gretz's method is used with (11). We represent the solution as

$$P(\xi,\ \eta)=P_\infty(\xi)+P_0(\xi,\ \eta),$$
$$P_\infty(\xi)=\lim_{\eta\to\infty}P(\xi,\ \eta),\qquad \lim_{\eta\to\infty}P_0(\xi,\ \eta)=0,\tag{13}$$

i.e., $P_\infty(\xi)$ is the solution on the stabilized heat-transfer part (nominally $\eta\to\infty$), while $P_0(\xi,\ \eta)$ is the solution on the initial thermal segment.

For the stabilized heat-transfer segment,

$$\frac{d}{d\xi}\left[F(\xi)\frac{\partial P_\infty}{\partial\xi}\right]-\gamma_T^2P_\infty F(\xi)=0,$$

$$\left(\frac{\partial P_\infty}{\partial\xi}\right)_{\xi=0}=-1,\qquad\left(\frac{dP_\infty}{d\xi}\right)_{\xi=1}=0.\tag{14}$$

The pivot method was applied to the boundary-value problem of II type in (14). Values were tabulated for $P_\infty(0)\equiv P_\infty(\xi=0)$, $P_\infty(1)\equiv P_\infty(\xi=1)$ and $\overline{P}_\infty$, with the mean mass values determined from

$$\overline{P}_\infty=\frac{\int_0^1 P_\infty F(\xi)f(\xi)\,d\xi}{\int_0^1 F(\xi)f(\xi)\,d\xi}=\frac{2G(1-k)}{1+k}\int_0^1 P_\infty F(\xi)f(\xi)\,d\xi.\tag{15}$$

Integrating (14) gives

$$\int_0^1 P_\infty F(\xi)\,d\xi=\frac{R_1}{\gamma_T^2}\equiv\frac{k}{1-k}\,\frac{1}{\gamma_T^2},\tag{16}$$

which has been used to analyze the errors in the numerical solution along with

$$\int_0^1 F(\xi)f(\xi)\,d\xi=\frac{1}{2G}(R_2^2-R_1^2)\equiv\frac{1}{2G}\,\frac{(1+k)}{(1-k)}.$$

We introduce the fitting functions

$$\overline{\Phi} = \frac{G\overline{P}}{\overline{\Theta}_f}, \quad \Phi(0) = \frac{GP(0)}{\Theta_f(0)}, \quad \Phi(1) = \frac{GP(1)}{\Theta_f(1)},$$

$$S = \frac{G\,\mathrm{Nu}_{f1}}{2}[P(0) - \overline{P}] \equiv \frac{\mathrm{Nu}_{f1}}{2}[\Theta_f(0)\Phi(0) - \overline{\Theta}_f\overline{\Phi}], \tag{17}$$

$$S_{\mathrm{ad}} = \frac{G[P(1) - \overline{P}]}{2\Theta^*_{f\,\mathrm{ad}}} \equiv \frac{\Theta_f(1)\Phi(1) - \overline{\Theta}_f\overline{\Phi}}{2\Theta^*_{f\,\mathrm{ad}}}.$$

Then the theoretical expressions for the transfer characteristics in the stabilized heat-transfer part are

$$\overline{\Theta}_\infty = \frac{\overline{\Theta}_{f\infty}}{1+\varkappa}(1 + \varkappa\overline{\Phi}_\infty); \quad \overline{Y}_\infty = \frac{\overline{\Theta}_{f\infty}\varkappa}{1+\varkappa}(1 - \overline{\Phi}_\infty);$$

$$\Theta_\infty(0) = \frac{\Theta_{f\infty}(0)}{1+\varkappa}(1 + \varkappa\Phi_\infty(0)); \quad Y_\infty(0) = \frac{\Theta_{f\infty}(0)\varkappa}{1+\varkappa}(1 - \Phi_\infty(0));$$

$$\Theta_\infty(1) = \frac{\Theta_{f\infty}(1)}{1+\varkappa}(1 + \varkappa\Phi_\infty(1)); \quad Y_\infty(1) = \frac{\Theta_{f\infty}(1)\varkappa}{1+\varkappa}(1 - \Phi_\infty(1)); \tag{18}$$

$$\mathrm{Nu}_{1\infty} = \frac{(1+\varkappa)\mathrm{Nu}_{f1\infty}}{1 + \varkappa S_\infty}; \quad \Theta^*_{\mathrm{ad}\infty} = \frac{\Theta^*_{f\,\mathrm{ad}\infty}}{1+\varkappa}(1 + \varkappa S_{\mathrm{ad}\infty}),$$

in which

$$\overline{\Theta}_{f\infty} \equiv \overline{\Theta}_f = 2\eta\frac{k}{1+k}; \quad \Theta_{f\infty}(0) = \overline{\Theta}_f + \frac{2}{\mathrm{Nu}_{f1\infty}}; \quad \Theta_{f\infty}(1) = \overline{\Theta}_f + 2\Theta^*_{f\,\mathrm{ad}\infty}. \tag{19}$$

It follows from (18) that the characteristics can be calculated for this turbulent reacting flow in an annular channel from data on the heat transfer in a chemically inert (frozen) flow.

The heat-transfer equation for a turbulent flow of inert coolant in an annular channel is as follows subject to the usual simplifying assumptions [4] for analytic solution

$$f(R)\frac{\partial\Theta_f}{\partial\eta} = \frac{1}{R}\frac{\partial}{\partial R}\left[Rg(R)\frac{\partial\Theta_f}{\partial R}\right],$$

$$\Theta_f(R,\ 0) = 0, \quad \left(\frac{\partial\Theta_f}{\partial R}\right)_{R_1} = -1, \quad \left(\frac{\partial\Theta_f}{\partial R}\right)_{R_2} = 0. \tag{20}$$

We introduce the (10) coordinate and the function

$$P_f = \frac{\Theta_f}{G}, \tag{21}$$

to rewrite (20) as

$$G^2F(\xi)f(\xi)\frac{\partial P_f}{\partial\eta} = \frac{\partial}{\partial\xi}\left[F(\xi)\frac{\partial P_f}{\partial\xi}\right];$$

$$P_f(\xi,\ 0) = 0, \quad \left(\frac{\partial P_f}{\partial\xi}\right)_{\xi=0} = -1, \quad \left(\frac{\partial P_f}{\partial\xi}\right)_{\xi=1} = 0. \tag{22}$$

We represent the solution for the heat transfer in an inert flow as a sum of solutions for the stabilized heat-transfer part and the initial thermal segment:

$$P_f(\xi,\ \eta) = P_{f\infty} + P_{f0}. \tag{23}$$

For the stabilized heat-transfer segment

$$P_{f\infty}(\xi,\ \eta) = P_{f1}(\eta) + P_{f2}(\xi), \tag{24}$$

in which

$$P_{f1}(\eta) = \frac{\overline{\Theta}_f}{G}; \quad \overline{\Theta}_f = 2\eta \frac{k}{1+k}; \quad P_{f2}(\xi) = h_f(\xi). \tag{25}$$

We substitute (23)-(25) into (22) to get a boundary-value problem of the second kind for the stabilized heat-transfer part:

$$G\frac{2k}{1+k}F(\xi)f(\xi) = \frac{d}{d\xi}\left[F(\xi)\frac{dh_f}{d\xi}\right],$$
$$\left(\frac{dh_f}{d\xi}\right)_{\xi=0} = -1, \quad \left(\frac{dh_f}{d\xi}\right)_{\xi=1} = 0. \tag{26}$$

We integrate (26) as in [4] and use

$$\overline{h}_f = \frac{\int\limits_0^1 h_f F f d\xi}{\int\limits_0^1 F f d\xi} = 0, \tag{27}$$

to get

$$h_f(1) = \frac{2k}{1+k}\left[\frac{2G^2(1-k)}{1+k}\int\limits_0^1 \frac{d\xi\left(\int\limits_0^\xi F f d\xi\right)^2}{F} - G\int\limits_0^1 \frac{d\xi\left(\int\limits_0^\xi F f d\xi\right)}{F}\right]; \tag{28}$$

$$h_f(0) = \frac{4G^2k(1-k)}{(1+k)^2}\int\limits_0^1 \frac{d\xi\left(\int\limits_\xi^1 F f d\xi\right)^2}{F}. \tag{29}$$

We use (21) and (24)-(29) to derive expressions for the transfer characteristics on such turbulent flow of an inert material:

$$\Theta_{f\infty}(0) = \overline{\Theta}_f + Gh_f(0), \quad \overline{\Theta}_f = 2\eta\frac{k}{1+k}, \quad \mathrm{Nu}_{f1\infty} = \frac{2}{Gh_f(0)},$$
$$\Theta_{f\infty}(1) = \overline{\Theta}_f + Gh_f(1), \quad \Theta_{f\,\mathrm{ad}\infty} = \frac{1}{2}Gh_f(1). \tag{30}$$

To calculate the (17) functions and the (18) characteristics, we use a velocity profile derived from the equation of motion [5]

$$f_i = (-1)^{i-1}\left(\frac{\xi_{\mathrm{TP}}\mathrm{Re}}{16}\right)\int\limits_{R_i}^{R}\frac{R_m^2 - R^2}{Rg_{\mathrm{r}}}dR, \tag{31}$$

in which i = 1 corresponds to the inner region of the flow ($R_1 \leqslant R \leqslant R_m$) and i = 2 to the outer ($R_m \leqslant R \leqslant R_2$). The hydraulic resistance coefficient was taken [6] as $\xi_{fr} = [1.82 \lg \mathrm{Re} - 1.64 - 0.19 k^{0.25}]^{-2}$.

The maximum-velocity coordinate was derived from the formula [7] with a revised power [6]:

$$R_m = \frac{k + k^n}{(1-k)(1+k^n)}, \quad n = 0{,}3 + 0{,}043 \lg(\mathrm{Re}\cdot 10^{-4}). \tag{32}$$

A modified Reichardt formula for a circular tube with variable parameters was used to derive the turbulent viscosity, which involves the geometry and the hydrodynamics in the annular channel [6]:

$$\frac{\nu_t}{\nu} = \frac{0{,}4225}{6}\left(y_i^+ + y_\ell^+ \operatorname{th}\frac{y_i^+}{y_\ell^+}\right)(1+\eta_i^+)(1+2\eta_i^{+2}), \qquad (33)$$

in which

$$\eta_i^+ = \left|\frac{R_m - R}{R_m - R_i}\right|, \quad y_\ell^+ = 11 + \exp(-3\cdot 10^{-4}\,\mathrm{Re}),$$

$$y_i^+ = \frac{V_i^*}{\nu}(r - r_i)(-1)^{i-1} \equiv (-1)^{i-1}(R - R_i) \times \sqrt{\frac{\xi_{fr}}{8}\frac{\mathrm{Re}}{2}}\sqrt{(-1)^{i-1}\frac{R_m^2 - R_i^2}{R_i}}.$$

A discontinuity occurs on the R_m line when (33) is used. To obtain a continuous function ν_t/ν throughout the cross section, we use the following link-up methods:

$$\begin{aligned} &\text{for } 0 \leqslant y_1^+ \leqslant y_{1m}^+ &&\text{put} \quad (\nu_t/\nu)_1 = (\nu_t/\nu)_{1\mathrm{Reich}},\\ &\text{for } 0 \leqslant y_2^+ \leqslant y_{2\ell i}^+ &&\text{put} \quad (\nu_t/\nu)_2 = (\nu_t/\nu)_{2\mathrm{Reich}},\\ &\text{for } y_{2\ell i}^+ \leqslant y_2^+ \leqslant y_{2m}^+ &&\text{put} \quad (\nu_t/\nu)_2 = (\nu_t/\nu)_{2\mathrm{Reich}} - C_2, \end{aligned} \qquad (34)$$

where

$$C_2 = \Delta\left(\frac{\nu_t}{\nu}\right)_{R_m} \frac{(R_{\ell i} - R_1) - (R - R_1)}{(R_{\ell i} - R_1) - (R_m - R_1)}; \quad (R_{\ell i} - R_1) = 1{,}4\,(R_m - R_1);$$

$$\Delta\left(\frac{\nu_t}{\nu}\right)_{R_m} = \left[\left(\frac{\nu_t}{\nu}\right)_{2R_m} - \left(\frac{\nu_t}{\nu}\right)_{1R_m}\right]_{\mathrm{Reich}}.$$

The resulting values for the continuous function of ν_t/ν agree with measurements [8] with a maximum error of 8-11% for the inner region (i = 1) and 4-6% for the outer (i = 2) throughout the range examined in [8]: $\mathrm{Re} = 4.10^4\text{-}1.8\cdot 10^5$, k = 0.28-0.75.

One can compare these results from (30)-(34) with $\mathrm{Pr}_f = 0.7$ abd $\mathrm{Pr}_t = 0.8$ with the observed and calculated values from various sources [7, 9-12]; this implies that $|\delta \mathrm{Nu}_{f1\infty}|_{\max} \leqslant 7\%$ and $|\delta\Theta^*_{\mathrm{ad}\infty}|_{\max} \leqslant 11\%$ for $k = 0{,}1\text{—}0{,}8$, $\mathrm{Re} = 2\cdot 10^4\text{—}10^6$. When the fitted functions are calculated for the characteristics in a turbulent reacting flow from (17), we use approximations [9, 12] for $\mathrm{Nu}_{f1\infty}$ and $\Theta^*_{\mathrm{ad}\infty}$.

The (17) functions are dependent on $\mathrm{Pr}_f/\mathrm{Pr}_t$, k, Re, γ. With fixed values $\mathrm{Pr}_f/\mathrm{Pr}_t = 0.7/0.8$, $\mathrm{Re} = 10^4\text{-}10^6$, k = 0.1-0.9, we tabulated values of $\bar{\Phi}_\infty$, $\Phi_\infty(0)$, $\Phi_\infty(1)$, S_∞, $S_{\mathrm{ad}\infty}$ as functions of γ in the range 0 to 5×10^3 (from the chemically frozen state to the equilibrium one). The fitted functions varied from 1 (frozen) to 0 local thermochemical equilibrium). For convenience in using the results, the tabulated values for k = 0.3-0.9, $\mathrm{Re} = 10^4\text{-}10^6$, $\gamma = 5\text{-}5\cdot 10^3$ were fitted to

$$\bar{\Phi}_\infty = \frac{1 - \exp[-\gamma^2\eta(1 + 0{,}2Z^{-1})]}{\gamma^2\eta(1 + 0{,}2Z^{-1})}, \quad |\delta\bar{\Phi}|_{\mathrm{ap\,max}} \leqslant 7\%; \qquad (35)$$

$$S_\infty = \left(\frac{\operatorname{th} X}{X}\right)^n, \quad |\delta S_\infty|_{\mathrm{ap\,max}} \leqslant 5\%; \qquad (36)$$

$$S_{\mathrm{ad}\infty} = \frac{\operatorname{th}(by)}{by}, \quad |\delta S_{\mathrm{ad}\infty}|_{\mathrm{ap\,max}} \leqslant 6.5\%, \qquad (37)$$

which $Z = \mathrm{Re}/10^4$; $X = (a_0 + a_1 k + a_2 k^2)\gamma^p \mathrm{Re}^m$; $n = 1{,}109 + 4{,}238\cdot 10^{-2} Z - 3{,}847\cdot 10^{-4} Z^2$; $m = -0{,}7263 + 9{,}959\cdot 10^{-3} Z - 8{,}429\cdot 10^{-5} Z^2$; $p = 0{,}8040 - 2{,}842\cdot 10^{-2} Z + 2{,}495\cdot 10^{-4} Z^2$; $a_0 = 74{,}17 + 7{,}632 Z - 6{,}374\cdot 10^{-2} Z^2$; $a_1 = 68{,}95 - 0{,}5922 Z + 4{,}5\cdot 10^{-3} Z^2$; $a_2 = -39{,}10 + 0{,}5099 Z - 5{,}276\cdot 10^{-3} Z^2$; $y = \gamma \mathrm{Re}^{-0{,}4595}[1 + 0{,}082 Z]$; $b = 4{,}809 + 5{,}871 \exp(4{,}048\,y)$.

The fitting erros for (35)-(37) lead to the following error levels in determining the characteristics from (18): $|\delta\overline{\Theta}_\infty|_{\max}\leqslant 3\%$, $|\delta \mathrm{Nu}_\infty|_{\max}\leqslant 3\%$, $|\delta\Theta_{\mathrm{ad}\infty}|_{\max}\leqslant 4\%$.

Then (18) together with (35)-(37) give the heat and mass transfer coefficients with acceptable errors.

NOTTION

$R=r/\Delta$; $\eta=4z/d_e \mathrm{Re}\,\mathrm{Pr}$ dimensionless coordinates, ($d_e=2\Delta$, $\Delta=r_2-r_1$; $\mathrm{Re}=\overline{U}d_e/\nu$; $\mathrm{Pr}_f=\nu/a_f$; $a_f=\lambda_f/\rho C_{pf}$; $\Theta=(T-T_0)\Big/\left(\frac{q_{c1}\Delta}{\lambda_f}\right)$ dimensionless temperature; $Y^*=(x-x_{0e})\,\alpha'\Big/\left(\frac{q_{c1}\Delta}{\lambda_f}\right)$ dimensionless NO concentration; NO; $\alpha'=\Delta H_{mi}/C_{pf}\frac{M_A}{\rho}(2-x_e)$; $\Delta H_{mi}=2H_3+H_4-2H_2$ increment in molecular enthalpy on account of reaction $2NO_2\rightleftarrows 2NO+O_2$; $\varkappa=\alpha'(x_e-x_{0e})/(T-T_0)$ gas reactivity; $\beta^2=\tau_t/\tau_c$ Damkeller number; $\tau_d=\Delta^2/D_{23}$ characteristic diffusion time; $\tau_c^{-1}=nK_d(2-x_e)\,a_1$ chemical relaxation time; n = P/RT molar density; K_d nitrogen dioxide dissociation rate constant; x molar fraction of NO; $\gamma^2=\beta^2(1+\varkappa)$ chemical disequilibrium thermal parameter; $f(R)=U_z(R)/\overline{U}$ velocity profile; $g(R)=1+\frac{\nu_t}{\nu}\frac{\mathrm{Pr}_f}{\mathrm{Pr}_T}$; $k=r_1/r_2$; $R_1=\frac{k}{1-k}$; $R_2=\frac{1}{1-k}$; $gg=1+\frac{\nu_T}{\nu}$; $\Theta_{\mathrm{ad}\infty}=(T_\infty(1)-\overline{T}_\infty)\Big/\left(\frac{q_{c1}2\Delta}{\lambda_f}\right)$; y_i^+ dynamic coordinate; V_i^* dynamic velocity; $(V_i^*/V^*)^2=\tau_i/\overline{\tau}=\left(\frac{R_m^2}{R_i}-R_i\right)(-1)^{i-1}$, $\overline{\tau}=\rho\frac{\xi_{\mathrm{TP}}}{8}\overline{U}^2$; $y_{im}^+\equiv y_i^+(R=R_m)$; $(\nu_T/\nu)_{\mathrm{Reich}}$ calculation from (33); $y_{2\mathrm{cm}}^+\equiv y_2^+(R=R_{\mathrm{cm}})$ linkage coordinate in outer region; R_{1i} linkage radius; ξ integral coordinate, $\xi=\frac{1}{G}\int_0^R\frac{1}{\sqrt{g}}dR$, $G=\int_0^1\frac{1}{\sqrt{g}}dR$; $P(0)\equiv P(\xi=0)$, $P(1)\equiv P(\xi=1)$; subscripts: ∞ stabilized heat-transfer segment; f and e frozen and equilibrium states; M molar quantity; m coordinate for maximum velocity; and ap approximation error.

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