A GENERALIZED DIFFUSION THEORY OF BINARY HOMOGENEOUS MIXTURES. MIXTURE MOTION WITHIN AN INFINITE ROTATING CYLINDER

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The motion of single-temperature binary homogeneous mixtures is studied by using a generalized diffusion theory.

A generalized diffusion theory was proposed in [1] to describe the motion of homogeneous n-component mixtures of different temperatures. The fundamental equations were obtained to determine some characteristic velocity of a mixture u_α of the diffusion fluxes referred to this velocity, and other parameters.

The equations obtained are derived and studied in this paper in the case of single-temperature binary homogeneous mixtures for different characteristic velocities u_α. The motion of a liquid binary mixture within an infinite rotating cylinder is examined as a simple example.

1. Fundamental Equations of Motion of Binary Homogeneous Mixtures

Let there be a mixture consisting of two components with the densities ρ_1 and ρ_2, with the number of moles N_1 and N_2, with the molar masses M_1 and M_2 and with the molar partial volumes V_1 and V_2. Let us assume that a common temperature T is set in the mixture and there is no chemical reaction between the components.

Let us study the general motion of the mixture by using a certain characteristic velocity u_α, and the relative motions of the components by using generalized diffusion fluxes J_k^α. In practice, it is known that the "choice of a convenient reference system which governs what is to be understood by the common mixture velocity can greatly facilitate the computation and interpretation of the results" [2]. One of the following characteristic velocities is often used for homogeneous mixtures: the mean mass, volume, molar flow rate, and the velocity of one of the components. Depending on the specific conditions, some behavior of one of these velocities, e.g., its magnitude [2,3] or direction, can be "predicted" in many practical problems. This explains why the mean mass flow rate of a mixture is not always most convenient for the solution of problems. It is hence necessary to use other characteristic velocities to formulate the fundamental laws of mixture motion.

The main system of equations to determine u_α, J_k^α, and T has the form [1]

$$u_a = \sum_{k=1}^{2} a_k u_k, \quad J_1^a = \rho_1 (u_1 - u_a), \quad J_2^a = -(\rho_2 a_1 / a_2 \rho_1) J_1^a,$$

$$\frac{\partial \rho_k}{\partial t} + \bar{\nabla} \cdot (\rho_k u_a) = -\nabla \cdot J_k^a, \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u_a) = -\nabla \cdot \sum_{k=1}^{2} J_k^a,$$

$$\rho \frac{d^{(a)} u_a}{dt} = \rho f - \nabla p + \nabla \cdot \tau_a - \sum_{k=1}^{2} \frac{D^{(a)} J_k^a}{Dt}, \quad \tau_a = \frac{\lambda_a}{T} (\nabla \cdot u_a) I + \frac{2\mu_a}{T} e_a, \tag{1.1}$$

$$\frac{D^{(a)} J_1^a}{Dt} = Q_1^a = -T \frac{\rho_1^2 a_2^2}{\alpha_{11}^a (\rho_1 a_2^2 + \rho_2 a_1^2)} \Big\{ J_1^a + [\alpha_1^a - \alpha_{11}^a \Big(h_1 -$$

$$- \frac{a_1 \rho_2}{a_2 \rho_1} h_2 \Big)] \frac{\nabla T}{T^2} - \left(v_1 - \frac{a_1 \rho_2}{a_2 \rho_1} \right) \nabla p - \frac{\alpha_{11}^a}{T} \Big[f_1 - \frac{a_1 \rho_2}{a_2 \rho_1} f_2 - \left(1 - \frac{a_1 \rho_2}{a_2 \rho_1} \right) \times$$

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$$\times \frac{d^{(a)}u_a}{dt} - \left(1+\frac{a_1}{a_2}\right)(\nabla\mu_1) + \frac{a_1\rho_2}{a_2\rho_1}\sum_{k=1}^{2} J_k^a \frac{d^{(a)}}{dt}\left(\frac{a_k}{\rho_k}\right)\Bigg]\Bigg\},$$

$$-\left[q+\left(1-\frac{a_1\rho_2}{a_2\rho_1}\right)J_1^a\right] \doteq \left[\alpha^a - \alpha_1^a\left(h_1 - \frac{a_1\rho_2}{a_2\rho_1}h_2\right)\right]\frac{\nabla T}{T^2} +$$

$$+\frac{\alpha_1^a}{T}\Bigg\{f_1 - \frac{a_1\rho_2}{a_2\rho_1}f_2 - \left(1-\frac{a_1\rho_2}{a_2\rho_1}\right)\frac{d^{(a)}u_a}{dt} - \left(1+\frac{a_1}{a_2}\right)(\nabla\mu_1)_{p,T} -$$

$$-\left(v_1 - \frac{a_1\rho_2}{a_2\rho_1}v_2\right)\nabla p - \left(1+\frac{\rho_2 a_1^2}{\rho_1 a_2^2}\right)\frac{Q_1^a}{\rho_1} - \frac{a_1\rho_2}{a_2\rho_1}\sum_{k=1}^{2} J_k^a \frac{d^{(a)}}{dt}\left(\frac{a_k}{\rho_k}\right)\Bigg\}.$$

The quantities a_1, a_2 in (1.1) are normalized weights which we use to obtain the mean mixture velocity u_a; f_1, f_2, mass forces acting on unit mass of each component; h_1 and h_2, enthalpies per unit mass of each component; v_1 and v_2, partial specific volumes; p, equilibrium pressure; τ_a, viscous stress tensor; e_a, strain rate tensor; h^*, heat source; and μ_1 and μ_2, chemical potentials. The operation $(\cdot)$ denotes the scalar product and $(\cdot\cdot)$ convolution in both diad indices. The derivatives $d^{(a)}/dt$ and $D^{(a)}/Dt$ have the form

$$\frac{d^{(a)}}{dt}(\ldots) = \frac{\partial}{\partial t}(\ldots) + (u_a\cdot\nabla)(\ldots),$$

$$\frac{D^{(a)}}{Dt}(\ldots) = \frac{d^{(a)}}{dt}(\ldots) + [(\ldots)\cdot\nabla]u_a + (\ldots)(\nabla\cdot u_a). \tag{1.2}$$

Given the normalized weights a_k and the thermodynamic functions, system (1.1) is adequate for finding the desired quantities. We write this system of equations below for specific values of a_k.

Mean Mass Flow Rate ($a_k = c_k$). In this case system (1.1) becomes

$$\frac{\partial\rho_k}{\partial t} + \nabla(\rho_k u_m) = -\nabla J_k^m, \quad \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho u_m) = 0,$$

$$\rho\frac{d^{(m)}u_m}{dt} = \rho f - \nabla p + \nabla\cdot\tau_m, \quad \tau_m = \frac{\lambda_m}{T}(\nabla\cdot u_m)I + \frac{2\mu_m}{T}e_m,$$

$$\frac{D^{(m)}J_1^m}{Dt} = Q_1^m = -T\frac{\rho_1\rho_2}{\rho\alpha_{11}^m}\left\{J_1^m + [\alpha_1^m - \alpha_{11}^m(h_1-h_2)]\frac{\nabla T}{T^2} - \frac{1}{T}\alpha_{11}^m\left[(f_1-f_2) - \frac{\rho}{\rho_2}(\nabla\mu_1)_{p,T} - (v_1-v_2)\nabla p\right]\right\}, \tag{1.3}$$

$$-q = [\alpha^m - \alpha_1^m(h_1-h_2)]\frac{\Delta T}{T^2} + \frac{1}{T}\alpha_1^m\left\{(f_1-f_2) - \frac{\rho}{\rho_2}(\nabla\mu_1)_{p,T} - (v_1-v_2)\nabla p - \frac{\rho}{\rho_1\rho_2}Q_1^m\right\}.$$

Mean Volume Flow Rate ($a_k = \rho_k v_k$). If the mean volume flow rate is taken as the characteristic velocity u_a, then we obtain in place of (1.3)

$$\frac{\partial\rho_k}{\partial t} + \nabla\cdot(\rho_k u_v) = -\nabla\cdot J_k^v, \quad \nabla\cdot u_v = \sum_{k=1}^{2}\rho_k\frac{d^{(k)}v_k}{dt},$$

$$\rho\frac{d^{(v)}u_v}{dt} = \rho f - \nabla p + \nabla\cdot\tau_v - \sum_{k=1}^{2}\frac{D^{(v)}J_k^v}{Dt}, \quad \tau_v = \frac{\lambda_v}{T}(\nabla\cdot u_v)I + \frac{2\mu_v}{T}e_v,$$

$$\frac{D^{(v)}J_1^v}{Dt} = Q_1^v = -T\frac{\rho_1\rho_2 v_2^2}{\alpha_{11}^v(\rho_1 v_1^2 + \rho_2 v_2^2)}\Bigg\{J_1^v + \left[\alpha_1^v - \alpha_{11}^v\left(h_1 - \frac{v_1}{v_2}h_2\right)\right]\frac{\nabla T}{T^2} - \tag{1.4}$$

$$-\frac{1}{T}\alpha_{11}^v\left[\left(f_1 - \frac{v_1}{v_2}f_2\right) - \left(1-\frac{v_1}{v_2}\right)\frac{d^{(v)}u_v}{dt} - \frac{1}{\rho_2 v_2}(\nabla\mu_1)_{p,T} + \frac{v_1}{\rho_2 v_2^2}\sum_{k=1}^{2}J_k^v\frac{d^{(v)}v_k}{dt}\right]\Bigg\},$$

$$-q = \left(1-\frac{v_1}{v_2}\right)J_1^v\varepsilon + \left[\alpha^v - \alpha_1^v\left(h_1 - \frac{v_1}{v_2}h_2\right)\right]\frac{\nabla T}{T^2} + \frac{1}{T}\alpha_1^v\Bigg(f_1 - \frac{v_1}{v_2}f_2\Bigg) -$$

$$-\left(1-\frac{v_1}{v_2}\right)\frac{d^{(v)}u^v}{dt} - \frac{1}{\rho_2 v_2}(\nabla\mu_1)_{p,T} - \frac{\rho_1 v_1^2 + \rho_2 v_2^2}{\rho_1\rho_2 v_2^2}Q_1^v - \frac{v_1}{\rho_2 v_2^2}\sum_{k=1}^{2}J_k^v\frac{d^{(v)}v_k}{dt}\Bigg].$$

Let us note that the specific partial volumes v_k can be considered constant [3] in many practical problems. Then system (1.4) simplifies. In particular, we obtain the following generalized compressibility condition:

$$\nabla u_v \equiv 0, \tag{1.5}$$

which yields additional advantages in solving problems by using the mean volume flow rate.

Mean Molar Flow Rate ($a_k = N_k/N$). The mean mixture molar flow rate u_μ is an important characteristic of mixture motion. By using it, the following system of equations can be obtained

$$\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k u_\mu) = -\nabla \cdot J_k^\mu, \quad \frac{\partial N}{\partial t} + \nabla \cdot (N u_\mu) = 0.$$

$$\rho \frac{d^{(\mu)} u_\mu}{dt} = \rho f - \nabla p + \nabla \cdot \tau_\mu - \sum_{k=1}^{2} \frac{D^{(\mu)} J_k^\mu}{Dt},$$

$$\tau_\mu = \frac{\lambda_\mu}{T} (\nabla \cdot u_\mu) I + \frac{2\mu_\mu}{T} e_\mu,$$

$$\begin{gathered}
\frac{D^{(\mu)} J_1^\mu}{Dt} = Q_1^\mu = -T \frac{N_1 N_2 M_1^2}{(N_1 M_2 + N_2 M_1)\alpha_{11}^\mu} \left\{ J_1^\mu + \left[\alpha_1^\mu - \alpha_{11}^\mu \left(h_1 - \frac{M_2}{M_1} h_2\right) \frac{\nabla T}{T} - \frac{1}{T} \alpha_{11}^\mu \left[\left(f_1 - \frac{M_2}{M_1} f_2\right) - \right.\right.\right. \\
\left.\left.\left. - \left(1 - \frac{M_2}{M_1}\right) \frac{d^{(\mu)} u_\mu}{dt} - \frac{N}{N_2} (\nabla \mu_1)_{p,T} - \left(v_1 - \frac{M_2}{M_1} v_2\right) \nabla p \right]\right]\right\}, \\
-q = \left(1 - \frac{M_2}{M_1}\right) J_1^\mu \varepsilon + \left[\alpha^\mu - \alpha_1^\mu \left(h_1 - \frac{M_2}{M_1} h_2\right)\right] \frac{\nabla T}{T^2} + \\
+ \frac{1}{T} \alpha_1^\mu \left[\left(f_1 - \frac{M_2}{M_1} f_2\right) - \left(1 - \frac{M_2}{M_1}\right) \frac{d^{(\mu)} u_\mu}{dt} - \frac{N}{N_2} (\nabla \mu_1)_{p,T} - \left(v_1 - \frac{M_2}{M_1} v_2\right) \nabla p - \frac{N_2 M_1 + N_1 M_2}{N_1 N_2 M_1^2} Q_1^\mu \right].
\end{gathered} \tag{1.6}$$

Velocity of the Second Component ($a_k = \delta_{k2}$). Cases exist when it is most convenient to use the velocity of one of the components as the characteristic mixture velocity. Let this velocity be u_2. Then we have the following system to find the desired quantities

$$\frac{\partial \rho_1}{\partial t} + \nabla \cdot (\rho_1 u_2) = -\nabla J_1, \quad \frac{\partial \rho_2}{\partial t} + \nabla \cdot (\rho_2 u_2) = 0,$$

$$\frac{\rho d^{(2)} u_2}{dt} = \rho f - \nabla p + \nabla \cdot \tau_2 - \frac{D^{(2)} J_1}{Dt}, \quad \tau_2 = \frac{\lambda}{T} (\nabla \cdot u_2) I + \frac{2\mu}{T} e_2,$$

$$\begin{gathered}
\frac{D^{(2)} J_1}{Dt} = Q_1 = -T \frac{\rho_1}{\alpha_{11}} \left\{ J_1 + (\alpha_1 - \alpha_{11} h_1) \frac{\nabla T}{T^2} - \frac{1}{T} \alpha_{11} \left[f_1 - \nabla (\mu_1)_{p,T} - v_1 \nabla p - \frac{d^{(2)} u_2}{dt} \right]\right\}, \\
-q = J_1 \varepsilon + (\alpha - \alpha_1 h_1) \frac{\nabla T}{T^2} + \frac{1}{T} \alpha_1 \left[f_1 - (\nabla \mu_1)_{p,T} - v_1 \nabla p - \frac{d^{(2)} u_2}{dt} - \frac{Q_1}{\rho_1} \right].
\end{gathered} \tag{1.7}$$

2. Motion of a Binary Fluid Mixture within an Infinite Cylinder

To illustrate the theory developed, let us examine the motion of a binary fluid mixture within an infinite rotating cylinder at a constant temperature and in the absence of external forces, as the simplest example. Moreover, the specific partial volumes will be considered constant.

Let an infinite cylinder rotate around its z axis at the constant angular velocity Ω, and let ρ_1° and ρ_2° be the densities of the components at the initial time. Find the distribution of these densities at later times.

It is most convenient to use the mean volume flow rate u_v to solve this problem since it is directed only in the θ direction in an (r, θ, z) cylindrical coordinate system. At the same time, other characteristic velocities are directed along both the θ and the r axes, which radically complicates the solution of the formulated problem.

The complete system of equations describing such mixture motion can be obtained from (1.4)-(1.5)

$$u_v=\{0;\ u_\theta(r,\ t);\ 0\},\quad J_1^v=J=\{J_r(r,\ t);\ J_\theta(r,\ t);\ 0\},$$

$$\frac{\partial\rho_1}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}(rJ_r),\quad \rho_2=\frac{1}{v_2}(1-\rho_1 v_1),$$

$$\frac{\partial u_\theta}{\partial t}=\nu\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(ru_\theta)\right]-\frac{1}{\rho}\left(1-\frac{v_1}{v_2}\right)\left[\frac{\partial J_\theta}{\partial t}+J_r\left(\frac{u_\theta}{r}+\frac{\partial u_\theta}{\partial r}\right)\right],$$

$$\frac{\partial J_r}{\partial t}-2\frac{J_\theta u_\theta}{r}=-T\frac{\rho_1\rho_2 v_2^2}{(\rho_1 v_1^2+\rho_2 v_2^2)\alpha_1^v}\left\{J_r+\frac{\alpha_{11}^v}{T}\left[-\left(1-\frac{v_1}{v_2}\right)\frac{u_\theta^2}{r}+\frac{\mu_{11}}{\rho_2 v_2}\frac{\partial\rho_1}{\partial r}\right]\right\},\tag{2.1}$$

$$\frac{\partial J_\theta}{\partial t}+J_r\left(\frac{u_\theta}{r}+\frac{\partial u_\theta}{\partial r}\right)=-T\frac{\rho_1\rho_2 v_2^2}{(\rho_1 v_1^2+\rho_2 v_2^2)\alpha_{11}^v}\left\{J_\theta+\frac{\alpha_{11}^v}{T}\left(1-\frac{v_1}{v_2}\right)\frac{\partial u_\theta}{\partial t}\right\},$$

$$\frac{1}{\rho}\frac{\partial p}{\partial r}=-\frac{u_\theta^2}{r}-\frac{1}{\rho}\left(1-\frac{v_1}{v_2}\right)\left(\frac{\partial J_r}{\partial t}-2\frac{J_\theta u_\theta}{r}\right).$$

The system of nonlinear partial differential equations (2.1) with the known phenomenological constants is sufficient for finding the six unknowns ρ_1, ρ_2, u_θ, J_θ, J_r, and p.

As $t\to\infty$, the following known results [3] can be obtained from (2.1):

$$u_\theta=\Omega r;\quad J_\theta=J_r=0,\quad \frac{dp}{dr}=\rho\Omega^2 r,\tag{2.2}$$

$$\frac{d\rho_1}{dr}=\frac{1}{\mu_{11}^\rho}\rho_2(v_2-v_1)\Omega^2 r,\quad \rho_2=\frac{1}{v_2}(1-\rho_1 v_1).$$

In the nonstationary case, we linearize (2.1) to obtain the analytic solution and we assume that the diffusion flux does not affect the mixture velocity distribution u_θ. We consequently obtain

$$\frac{\partial u_\theta}{\partial t}=\nu\frac{\partial}{\partial r}\left[r\frac{\partial}{\partial r}(ru_\theta)\right],\quad \frac{\partial\rho_1}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}(rJ_r),$$

$$\frac{\partial J_r}{\partial t}+KJ_r+KD\frac{\partial\rho_1}{\partial r}=KL\frac{u_\theta^2}{r},\quad \rho_2=\frac{1}{v_2}(1-\rho_1 v_1),\tag{2.3}$$

$$\frac{\partial J_\theta}{\partial t}+KJ_\theta=-KL\frac{\partial u_\theta}{\partial t},\quad \frac{\partial p}{\partial r}=\rho\frac{u_\theta^2}{r}-\left(1-\frac{v_1}{v_2}\right)\frac{\partial J_r}{\partial t}.$$

The constants K, D, L in (2.3) have the form

$$K=T\frac{\rho_1\rho_2 v_2^2}{(\rho_1 v_1^2+\rho_2 v_2^2)\alpha_{11}^v},\quad D=\frac{\alpha_{11}^v\mu_{11}^\rho}{T\rho_2 v_2},\quad L=\frac{1}{T}\alpha_{11}^v\left(1-\frac{v_1}{v_2}\right).\tag{2.4}$$

Let us note that we retain the term u_θ/r in (2.3) since it causes a redistribution of components along the r axis.

With conditions $u_\theta=0$ at $t=0$ and $u_\theta=\Omega R$ at $r=R$, the first equation of (2.3) yields the solution [4]

$$u_\theta(r,\ t)=\Omega r+2\Omega R\sum_{n=1}^{\infty}\frac{I_1\left(\lambda_n\frac{r}{R}\right)}{\lambda_n I_0(\lambda_n)}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right).\tag{2.5}$$

Here I_0 and I_1 are Bessel functions of the first kind of zero and first order, respectively, and λ_n are positive values satisfying $I_1(\lambda)=0$.

We henceforth limit ourselves to the following approximation for u_θ^2:

$$u_\theta^2\cong\Omega^2 r^2+2\Omega^2 Rr\sum_{n=1}^{\infty}\frac{I_1\left(\lambda_n\frac{r}{R}\right)}{\lambda_n I_0(\lambda_n)}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right).$$

Then the equation to find ρ_1, J_0, J_r has the form

$$\frac{\partial\rho_1}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}(rJ_r),\quad \frac{\partial J_\theta}{\partial t}+KJ_\theta=2KL\Omega\nu\sum_{n=1}^{\infty}\frac{\lambda_n I_1\left(\lambda_n\frac{r}{R}\right)}{RI_0(\lambda_n)}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right),\tag{2.6}$$

$$\frac{\partial J_r}{\partial t}+KJ_r+KD\frac{\partial\rho_1}{\partial r}=KL\Omega^2\left[r+2R\sum_{n=1}^{\infty}\frac{I_1\left(\lambda_n\frac{r}{R}\right)}{\lambda_n I_0(\lambda_n)}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right)\right.$$

If $K\to\infty$ in (2.6) (this case corresponds to neglecting $\partial J/\partial t$ in classical diffusion theory), then system (2.6) together with the conditions $J_r = 0$ at $t = 0$ and $J_r = 0$ at $r = R$ yields a solution of the form

$$J_\theta=2L\Omega\nu\sum_{n=1}^{\infty}\frac{\lambda_n}{R}\,\frac{I_1\left(\lambda_n\frac{r}{R}\right)}{I_0(\lambda_n)}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right),$$

$$J_r=\frac{2L\Omega^2\nu R}{\nu-D}\sum_{n=1}^{\infty}\frac{I_1\left(\lambda_n\frac{r}{R}\right)}{I_0(\lambda_n)}\left\{\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right)-\exp\left(-\lambda_n^2\frac{Dt}{R^2}\right)\right\},$$

$$\rho_1=\rho_1^0+\frac{L\Omega^2}{2D}\left(r^2-\frac{R^2}{2}\right)+$$

$$+\frac{2L\Omega^2R^2\nu}{\nu-D}\sum_{n=1}^{\infty}\frac{I_0\left(\lambda_n\frac{r}{R}\right)}{\lambda_n^2 I_0(\lambda_n)}\left\{\frac{1}{\nu}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right)-\frac{1}{D}\exp\left(-\lambda_n^2\frac{Dt}{R^2}\right)\right\}. \quad (2.7)$$

Under the condition $D \ll \nu$, we have for large t

$$\rho_1=\rho_1^0+\frac{L\Omega^2}{2D}\left(r^2-\frac{R^2}{2}\right)-\frac{2L\Omega R^2}{D}\sum_{n=1}^{\infty}\frac{I_0\left(\lambda_n\frac{r}{R}\right)}{\lambda_n^2 I_0(\lambda_n)}\exp\left(-\lambda_n^2\frac{Dt}{R^2}\right). \quad (2.8)$$

If $K\neq\infty$ in (2.6), i.e., it is impossible to neglect the term $\partial J_\theta/\partial t$, then system (2.6) must be solved in combination with the conditions $J_r = \partial J_r/\partial t = J_\theta = 0$ for $t = 0$, $J_r = 0$ for $r = R$.

In this case, for $K^2 - 4KD(\lambda_n^2/R^2) = \mu_n^2 \geq 0$ we find the following expression for ρ_1:

$$\rho_1=\rho_1^2+\frac{L}{2D}\Omega^2R^2\left(\frac{r^2}{R^2}-\frac{1}{2}\right)+\frac{2KL\Omega^2\nu}{R^2}\sum_{n=1}^{\infty}\frac{\lambda_n^2 I_0\left(\lambda_n\frac{r}{R}\right)}{\mu_n I_0(\lambda_n)}\left\{\frac{1}{-\frac{\lambda_n^2}{R^2}\nu+\frac{1}{2}(k-\mu_n)}\times\right.$$

$$\times\left[-\frac{R^2}{\lambda_n^2\nu}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right)+\frac{2}{K-\mu_n}\exp\left(-\frac{K-\mu_n}{2}t\right)\right]-$$

$$\left.-\frac{1}{-\frac{\lambda_n^2}{R^2}\nu+\frac{1}{2}(K+\mu_n)}\left[-\frac{R^2}{\lambda_n^2\nu}\exp\left(-\lambda_n^2\frac{\nu t}{R^2}\right)+\frac{2}{K+\mu_n}\exp\left(-\frac{K+\mu_n}{2}t\right)\right]\right\}. \quad (2.9)$$

The solution (2.9) differs from (2.7) only at the initial times, while (2.9) and (2.7) tend to a common distribution as $t\to\infty$, of the form

$$\rho_1=\rho_1^0+\frac{\rho_2^0(v_2-v_1)}{\mu_{11}^0}\Omega^2R^2\left(\frac{r^2}{R^2}-\frac{1}{2}\right).$$

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