

EXISTENCE AND UNIQUENESS OF THE SOLUTION
TO THE INITIAL BOUNDARY VALUE PROBLEM FOR
ONE-DIMENSIONAL ISOTHERMAL EQUATIONS OF
COMPRESSIBLE VISCOUS MULTICOMPONENT
MEDIA DYNAMICS

A.E. MAMONTOV , D.A. PROKUDIN , D.A. ZAKORA 

Представлено О.С. Розановой

Abstract: An initial boundary value problem is considered for one-dimensional equations of the dynamics of compressible multicomponent media. A global theorem of existence and uniqueness of a strong solution is proved without restrictions on the structure of the viscosity matrix except for the standard properties of symmetry and positivity.

Keywords: compressible viscous medium, multicomponent flows, viscosity matrix, boundary value problem, existence and uniqueness theorem.

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1 Introduction

Modelling the motion of multi-component media and solving the mathematical problems arising is of great interest to both physics and mathematics. However it is little-studied, and no unified approach to this field has been developed so far, and no mathematical theory has been constructed concerning the existence, uniqueness and properties of solutions of the initial-boundary value problems that arise in the process of modelling. A detailed survey of this problem area can be obtained from the monographs [1, 2] and the papers [3, 4]. In this paper we choose to study one of the numerous versions of modelling the motion of multi-component fluid mixtures, namely, a homogeneous mixture of viscous compressible fluids with multiple velocities. This means that all the components (constituents) of the mixture are present in the same phase at every point of space, but each of them has its own local velocity of motion; the components interact via momentum exchange and viscous friction (and also heat exchange in heatconducting models). The model under consideration is a generalization of the well-known Navier—Stokes system of equations describing the motions of compressible viscous single-component media and includes the continuity and momentum equations, and also the energy equation(s) in heatconducting models. The characteristic feature of these equations, in addition to their nonlinearity, is the presence of higher order derivatives of the velocities of all components in the momentum (and energy) conservation laws, due to the composite structure of the viscous stress tensors [1, 2, 5, 6, 7, 8, 9]. This specificity of multicomponent flows can be described using the concept of viscosity matrix. Unlike the single-component case in which the viscosity is scalar-valued, in the multicomponent case the viscosities form a matrix whose entries describe viscous friction. Diagonal entries describe viscous friction within each component, and non-diagonal entries describe friction between the components. In the case of a diagonal viscosity matrix, the momentum equations are possibly connected via the lower order terms only. In the paper the more complicated case of off-diagonal viscosity matrices is under consideration. The aim of the paper is to analyze the existence and uniqueness of solution to an initial-boundary value problem for isothermal (non-heatconducting) equations of compressible viscous multicomponent media in the case of one-dimensional motions in a bounded domain with non permeable boundaries.

As mentioned above, the multi-velocity model of compressible viscous multicomponent media dynamics under consideration is a generalization of the well-known Navier—Stokes system of equations and hence the mathematical results for multicomponent media appeared after the progress achieved in the Navier—Stokes theory, for which an invaluable contribution has been made by one-dimensional results [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35]. The unique solvability of the considered one-dimensional equations of compressible viscous multicomponent media in the polytropic case is investigated in [36, 37]. Similar issues

for related models of multicomponent media are discussed in [38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50]. Spectral analysis of some linear models of compressible viscous multicomponent media is carried out in [51, 52].

The structure of the paper is as follows. Section 2 contains the statement of the initial-boundary value problem and the formulation of the main result which is Theorem 1 concerning the existence and uniqueness of the solution. In Section 3, we study the solvability of an approximate initial-boundary value problem which is obtained from the original one via Galerkin method. In Section 4, the solutions to the approximate problem are estimated uniformly in the approximation parameter. Basing on these estimates, in Section 5 the limit transition is made and the local-in-time existence of a solution to the original initial-boundary value problem is verified. In order to continue the local solution, in Section 6 we prove a priori estimates, in which the constants do not depend on the local existence interval. In Section 7, the uniqueness of the solution to the initial-boundary value problem is proved.

2 Statement of the initial-boundary value problem and formulation of the existence and uniqueness theorem

We consider the initial boundary value problem for one-dimensional isothermal equations of the dynamics of compressible viscous multicomponent media. In the closure \bar{Q}_T of a domain $Q_T = (0, T) \times (0, 1)$ ($T > 0$) the sought values are the densities $\rho_i(t, x) > 0$ and the velocities $u_i(t, x)$ of each component with the number $i = 1, \dots, N$ ($N \in \mathbb{N}$, $N \geq 2$), which satisfy the following system of differential equations, initial and boundary conditions:

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial(\rho_i v)}{\partial x} = 0, \quad i = 1, \dots, N, \quad (1)$$

$$\rho_i \left(\frac{\partial u_i}{\partial t} + v \frac{\partial u_i}{\partial x} \right) + \alpha_i K \frac{\partial \rho}{\partial x} = \sum_{j=1}^N \nu_{ij} \frac{\partial^2 u_j}{\partial x^2}, \quad i = 1, \dots, N, \quad (2)$$

$$\rho_i|_{t=0} = \rho_{0i}(x), \quad u_i|_{t=0} = u_{0i}(x), \quad i = 1, \dots, N, \quad (3)$$

$$u_i|_{x=0} = u_i|_{x=1} = 0, \quad i = 1, \dots, N. \quad (4)$$

Here v is the average velocity, $v = \sum_{j=1}^N \alpha_j u_j$, $\alpha_j = \text{const} \in (0, 1)$, $\sum_{j=1}^N \alpha_j = 1$,

ρ is the total density, $\rho = \sum_{j=1}^N \rho_j$, constant viscosity coefficients ν_{ij} form the matrix $\mathbf{N} > 0$, the coefficient $K > 0$, the initial data $\rho_{0i}(x)$, $u_{0i}(x)$, $i = 1, \dots, N$ are given.

The given model corresponds to the so-called diffusion approximation appropriate at description of motions in which relative velocities of components are small in comparison with the general (average) velocity of the flow (mixture).

Definition 1. By a strong solution to problem (1)–(4) we mean $2N$ functions $(\rho_1, \dots, \rho_N, u_1, \dots, u_N)$ such that for all $i = 1, \dots, N$

$$\begin{aligned} \rho_i > 0, \quad \rho_i \in L_\infty(0, T; W_2^1(0, 1)), \quad \frac{\partial \rho_i}{\partial t} \in L_\infty(0, T; L_2(0, 1)), \\ u_i \in L_\infty(0, T; W_2^1(0, 1)) \cap L_2(0, T; W_2^2(0, 1)), \quad \frac{\partial u_i}{\partial t} \in L_2(Q_T), \end{aligned} \quad (5)$$

equations (1), (2) are satisfied almost everywhere in Q_T , the initial conditions (3) are valid for almost all $x \in (0, 1)$, and the boundary conditions (4) are accepted for almost all $t \in (0, T)$.

Theorem 1. Let the initial data in (3) satisfy the conditions

$$\rho_{0i} > 0, \quad \rho_{0i} \in W_2^1(0, 1), \quad u_{0i} \in \overset{\circ}{W}_2^1(0, 1), \quad i = 1, \dots, N. \quad (6)$$

Then there exists a unique strong solution to problem (1)–(4) in the sense of Definition 1.

Proof of Theorem 1 is given in Sections 3–7.

3 Construction of Galerkin approximations

Let us first prove the solvability of an approximate initial-boundary value problem, obtained from problem (1)–(4) by applying the Galerkin method (in the spatial variable x) to equations (2).

Theorem 2. On the assumptions of Theorem 1 for all $m \in \mathbb{N}$ there is a time-interval $(0, t^m) \subset (0, T)$, where there exists a solution to the problem

$$\frac{\partial \rho_i^m}{\partial t} + \frac{\partial(\rho_i^m v^m)}{\partial x} = 0, \quad i = 1, \dots, N, \quad (7)$$

$$\int_0^1 \left(\rho_i^m \frac{\partial u_i^m}{\partial t} + \rho_i^m v^m \frac{\partial u_i^m}{\partial x} + \alpha_i K \frac{\partial \rho^m}{\partial x} - \sum_{j=1}^N \nu_{ij} \frac{\partial^2 u_j^m}{\partial x^2} \right) \sin(\pi k x) dx = 0, \quad (8)$$

$$i = 1, \dots, N, \quad k = 1, \dots, m,$$

$$\rho_i^m|_{t=0} = \rho_{0i}(x), \quad i = 1, \dots, N, \quad (9)$$

$$u_i^m = \sum_{s=1}^m \xi_{is}^m(t) \sin(\pi s x), \quad u_i^m|_{t=0} = \sum_{s=1}^m \xi_{0is}^m \sin(\pi s x), \quad i = 1, \dots, N, \quad (10)$$

$$\xi_{0is}^m := \xi_{is}^m(0) = 2 \int_0^1 u_{0i}(x) \sin(\pi s x) dx, \quad i = 1, \dots, N, \quad s = 1, \dots, m,$$

where $v^m = \sum_{j=1}^N \alpha_j u_j^m$, $\rho^m = \sum_{j=1}^N \rho_j^m$, and we have

$$\begin{aligned} \rho_i^m > 0, \quad \rho_i^m \in L_\infty(0, t^m; W_2^1(0, 1)) \cap W_\infty^1(0, t^m; L_2(0, 1)), \\ \xi_{is}^m \in C^1[0, t^m], \quad i = 1, \dots, N, \quad s = 1, \dots, m. \end{aligned} \quad (11)$$

Proof. We fix $t^m < T$. We omit the upper index m in the notations of the solutions up to the beginning of Section 5. Consider the set

$$V = \left\{ \boldsymbol{\xi} \in (C[0, t^m])^{mN} \mid \boldsymbol{\xi}(0) = \boldsymbol{\xi}_0, \|\boldsymbol{\xi}\|_{(C[0, t^m])^{mN}} \leq c \right\},$$

where

$$\begin{aligned} \boldsymbol{\xi} &= (\boldsymbol{\xi}_1, \dots, \boldsymbol{\xi}_N), \quad \boldsymbol{\xi}_i = (\xi_{i1}, \dots, \xi_{im}), \quad i = 1, \dots, N, \\ \boldsymbol{\xi}_0 &= (\boldsymbol{\xi}_{01}, \dots, \boldsymbol{\xi}_{0N}), \quad \boldsymbol{\xi}_{0i} = (\xi_{0i1}, \dots, \xi_{0im}), \quad i = 1, \dots, N, \end{aligned}$$

$$c^2 = e \frac{\max_{1 \leq i \leq N} \sup_{[0,1]} \rho_{0i}}{\min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}} \|\boldsymbol{\xi}_0\|_{\mathbb{R}^{mN}}^2 + 1.$$

We construct the operator $A: V \rightarrow (C[0, t^m])^{mN}$, $\text{Im } A \subset (C^1[0, t^m])^{mN}$, $A(\boldsymbol{\xi}) = \boldsymbol{\psi}$, where $\boldsymbol{\psi} = (\boldsymbol{\psi}_1, \dots, \boldsymbol{\psi}_N)$, $\boldsymbol{\psi}_i = (\psi_{i1}, \dots, \psi_{im})$, $i = 1, \dots, N$, by the following algorithm. First, we find the functions

$$\rho_i > 0, \quad \rho_i \in L_\infty(0, t^m; W_2^1(0, 1)) \cap W_\infty^1(0, t^m; L_2(0, 1)), \quad i = 1, \dots, N$$

as solutions to the Cauchy problems (7), (9), where $v = \sum_{j=1}^N \alpha_j u_j$, and u_j , $j = 1, \dots, N$ are given by (10) (see [53]). Moreover, the inequalities

$$\left(\inf_{[0,1]} \rho_{0i} \right) e^{-\sum_{j=1}^N \int_0^t \sup_{[0,1]} \left| \frac{\partial u_j}{\partial x} \right| d\tau} \leq \rho_i(t, x) \leq \left(\sup_{[0,1]} \rho_{0i} \right) e^{\sum_{j=1}^N \int_0^t \sup_{[0,1]} \left| \frac{\partial u_j}{\partial x} \right| d\tau}, \quad (12)$$

$$i = 1, \dots, N$$

hold, which, in view of the inclusion $\boldsymbol{\xi} \in V$, give the estimates

$$\left(\inf_{[0,1]} \rho_{0i} \right) e^{-\pi m^2 c N t} \leq \rho_i(t, x) \leq \left(\sup_{[0,1]} \rho_{0i} \right) e^{\pi m^2 c N t}, \quad i = 1, \dots, N. \quad (13)$$

Next, we find $\boldsymbol{\psi}$ from the Cauchy problem for the system of mN ordinary first order differential (linear) equations:

$$\int_0^1 \left(\rho_i \frac{\partial U_i}{\partial t} + \rho_i v \frac{\partial U_i}{\partial x} + \alpha_i K \frac{\partial \rho}{\partial x} - \sum_{j=1}^N \nu_{ij} \frac{\partial^2 U_j}{\partial x^2} \right) \sin(\pi k x) dx = 0, \quad (14)$$

$$i = 1, \dots, N, \quad k = 1, \dots, m,$$

$$\boldsymbol{\psi}(0) = \boldsymbol{\xi}_0, \quad (15)$$

where $U_i = \sum_{s=1}^m \psi_{is}(t) \sin(\pi s x)$, $i = 1, \dots, N$. The inequality

$$\det M(t) \neq 0,$$

where

$$M(t) = \begin{pmatrix} M_1(t) & 0 & \dots & 0 \\ 0 & M_2(t) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & M_N(t) \end{pmatrix},$$

$$M_i(t) = \left\{ \int_0^1 \rho_i(t, x) \sin(\pi kx) \sin(\pi sx) dx \right\}_{k,s=1}^m, \quad i = 1, \dots, N,$$

which is valid due to the positivity of ρ_i , $i = 1, \dots, N$, admits to solve system (14) with respect to derivatives, which justifies the existence of $\psi \in (C^1[0, t^m])^{mN}$. Thus, for arbitrary $t^m \in (0, T]$ we can define the operator $A : V \rightarrow (C^1[0, t^m])^{mN} \subset (C[0, t^m])^{mN}$, $A(\xi) = \psi$, whose fixed point (if it exists), together with the corresponding functions ρ_i , u_i , $i = 1, \dots, N$, is a solution to problem (7)–(10).

We show that for sufficiently small t^m the operator A satisfies the assumptions of the Schauder theorem (see [21, P. 31]), i. e.

- (1) V is a convex closed bounded set (which is obvious in the case under consideration);
- (2) $A : V \rightarrow V$;
- (3) A is a completely continuous operator.

We first show that $A(V) \subset V$. Hereinafter, $C_i(\cdot)$, $i \in \mathbb{N}$, denote quantities which accept positive finite values depending on arguments indicated in the brackets or in comments. Multiplying equations (14) by $\psi_{ik}(t)$, summarizing with respect to i , k and integrating with respect to x , we obtain due to (7), that

$$\begin{aligned} \frac{1}{2} \frac{d}{dt} \left(\sum_{i=1}^N \int_0^1 \rho_i U_i^2 dx \right) + \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial U_i}{\partial x} \right) \left(\frac{\partial U_j}{\partial x} \right) dx = \\ = K \sum_{i=1}^N \alpha_i \int_0^1 \rho \left(\frac{\partial U_i}{\partial x} \right) dx, \end{aligned}$$

and taking into account the inequalities (to obtain them, we use (13) and the fact $\mathbf{N} > 0$)

$$\begin{aligned} \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial U_i}{\partial x} \right) \left(\frac{\partial U_j}{\partial x} \right) dx \geq C_1(\mathbf{N}) \sum_{i=1}^N \int_0^1 \left(\frac{\partial U_i}{\partial x} \right)^2 dx, \\ K \sum_{i=1}^N \alpha_i \int_0^1 \rho \left(\frac{\partial U_i}{\partial x} \right) dx \leq \frac{C_1}{2} \sum_{i=1}^N \int_0^1 \left(\frac{\partial U_i}{\partial x} \right)^2 dx + C_2, \end{aligned}$$

where $C_2 = \frac{K^2 N^3}{2C_1} \left(\max_{1 \leq i \leq N} \sup_{[0,1]} \rho_{0i} \right)^2 e^{2\pi m^2 c N t^m}$, we obtain the estimate

$$\frac{d}{dt} \left(\sum_{i=1}^N \int_0^1 \rho_i U_i^2 dx \right) + C_1 \sum_{i=1}^N \int_0^1 \left(\frac{\partial U_i}{\partial x} \right)^2 dx \leq 2C_2,$$

which, in its turn, leads to

$$\sum_{i=1}^N \int_0^1 \rho_i U_i^2 dx \leq \sum_{i=1}^N \int_0^1 \rho_{0i} U_{0i}^2 dx + 2C_2 t^m, \quad (16)$$

where $U_{0i} = \sum_{s=1}^m \psi_{is}(0) \sin(\pi s x) = \sum_{s=1}^m \xi_{0is} \sin(\pi s x)$, $i = 1, \dots, N$. Using (13) for the second time, we obtain from (16) the inequality

$$\|\psi\|_{(C[0,t^m])^{mN}}^2 \leq e^{\pi m^2 c N t^m} \frac{\max_{1 \leq i \leq N} \sup_{[0,1]} \rho_{0i}}{\min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}} \|\xi_0\|_{\mathbb{R}^{mN}}^2 + \frac{4C_2 e^{\pi m^2 c N t^m}}{\min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}} t^m.$$

Choosing

$$t^m < \min \left(T, \frac{1}{\pi m^2 c N}, \frac{\min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}}{4eC_3} \right), \quad (17)$$

where $C_3 = \frac{K^2 N^3 e^2}{2C_1} \left(\max_{1 \leq i \leq N} \sup_{[0,1]} \rho_{0i} \right)^2$, we obtain that $C_2 \leq C_3$, and arrive at the required estimate

$$\|\psi\|_{(C[0,t^m])^{mN}} \leq c.$$

Thus, if (17) holds, the operator A maps the set V to itself.

Let us prove the compactness of the operator A . Multiplying (14) by $\frac{d\psi_{ik}(t)}{dt}$, summarizing with respect to i, k and integrating with respect to x , we get the relation

$$\begin{aligned} \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial U_i}{\partial t} \right)^2 dx &= \sum_{i=1}^N \int_0^1 \left(-\rho_i v \left(\frac{\partial U_i}{\partial x} \right) \left(\frac{\partial U_i}{\partial t} \right) + \right. \\ &\quad \left. + \alpha_i K \rho \left(\frac{\partial^2 U_i}{\partial t \partial x} \right) - \sum_{j=1}^N \nu_{ij} \left(\frac{\partial^2 U_i}{\partial t \partial x} \right) \left(\frac{\partial U_j}{\partial x} \right) \right) dx. \quad (18) \end{aligned}$$

Let us estimate the terms on the right-hand side of (18) by using (13), the Cauchy inequality, and the inequalities $\|\xi\|_{(C[0,t^m])^{mN}} \leq c$, $\|\psi\|_{(C[0,t^m])^{mN}} \leq c$,

$$\begin{aligned}
 & \left\| \frac{\partial U_i}{\partial x} \right\|_{L_2(0,1)} \leq C_4(m) \|U_i\|_{L_2(0,1)}, \quad \left\| \frac{\partial^2 U_i}{\partial t \partial x} \right\|_{L_2(0,1)} \leq C_4 \left\| \frac{\partial U_i}{\partial t} \right\|_{L_2(0,1)}, \quad i = 1, \dots, N: \\
 & - \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial U_i}{\partial x} \right) \left(\frac{\partial U_i}{\partial t} \right) dx \leq \\
 & \leq \frac{1}{6} \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial U_i}{\partial t} \right)^2 dx + C_5 \left(C_4, \left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, c, m, t^m \right), \\
 & K \sum_{i=1}^N \alpha_i \int_0^1 \rho \left(\frac{\partial^2 U_i}{\partial t \partial x} \right) dx \leq \frac{1}{6} \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial U_i}{\partial t} \right)^2 dx + \\
 & + C_6 \left(C_4, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, \left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, K, N, c, m, t^m \right), \\
 & - \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial^2 U_i}{\partial t \partial x} \right) \left(\frac{\partial U_j}{\partial x} \right) dx \leq \\
 & \leq \frac{1}{6} \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial U_i}{\partial t} \right)^2 dx + C_7 \left(C_4, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, \mathbf{N}, N, c, m, t^m \right).
 \end{aligned}$$

Thus, from (18) we obtain the inequality

$$\frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial U_i}{\partial t} \right)^2 dx \leq C_5 + C_6 + C_7.$$

Integrating the last inequality in time and applying (13), we obtain the estimate

$$\sum_{i=1}^N \left\| \frac{\partial U_i}{\partial t} \right\|_{L_2(Q_{t^m})} \leq C_8 \left(C_5, C_6, C_7, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, c, m, t^m \right), \quad (19)$$

where $Q_{t^m} = (0, t^m) \times (0, 1)$. Thus, we have obtained the estimate for $\boldsymbol{\psi}$ in $(W_2^1(0, t^m))^{mN}$. Consequently, A is a compact operator.

We establish the continuity of the operator A from V in $(C[0, t^m])^{mN}$.

Let $\boldsymbol{\xi}^{(1,2)} \in V$, $\boldsymbol{\psi}^{(1,2)} = A(\boldsymbol{\xi}^{(1,2)})$, $u_i^{(1,2)} = \sum_{s=1}^m \xi_{is}^{(1,2)} \sin(\pi s x)$, $U_i^{(1,2)} =$

$\sum_{s=1}^m \psi_{is}^{(1,2)} \sin(\pi s x)$, $i = 1, \dots, N$. Let $\rho_i^{(1,2)}$, $i = 1, \dots, N$ be the solutions to

the Cauchy problems (7), (9), with v instead of $v^{(1,2)} = \sum_{j=1}^N \alpha_j u_j^{(1,2)}$ respectively. Denote $\rho_i = \rho_i^{(1)} - \rho_i^{(2)}$, $u_i = u_i^{(1)} - u_i^{(2)}$, $U_i = U_i^{(1)} - U_i^{(2)}$, $i = 1, \dots, N$, $v = v^{(1)} - v^{(2)}$, $\rho = \rho^{(1)} - \rho^{(2)}$, where $\rho^{(1,2)} = \sum_{j=1}^N \rho_j^{(1,2)}$. Differentiating the equations

$$\frac{\partial \rho_i^{(1,2)}}{\partial t} + \frac{\partial (\rho_i^{(1,2)} v^{(1,2)})}{\partial x} = 0, \quad i = 1, \dots, N \quad (20)$$

(see Remark 1 below) with respect to x , multiplying by $\frac{\partial \rho_i^{(1,2)}}{\partial x}$, integrating with respect to x, t , using the initial conditions

$$\rho_i^{(1,2)}|_{t=0} = \rho_{0i}, \quad i = 1, \dots, N, \quad (21)$$

the inequality (see (13))

$$\left(\inf_{[0,1]} \rho_{0i} \right) e^{-\pi m^2 c N t} \leq \rho_i^{(1,2)} \leq \left(\sup_{[0,1]} \rho_{0i} \right) e^{\pi m^2 c N t}, \quad i = 1, \dots, N \quad (22)$$

and Gronwall inequality we get

$$\left\| \frac{\partial \rho_i^{(1,2)}}{\partial x} \right\|_{L_2(0,1)} \leq C_9 \left(\left\{ \|\rho_{0i}\|_{W_2^1(0,1)} \right\}_{i=1}^N, N, c, m, t^m \right), \quad i = 1, \dots, N. \quad (23)$$

Let us note that (20), (21) lead to the equalities

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial (\rho_i v^{(1)})}{\partial x} + \frac{\partial (\rho_i^{(2)} v)}{\partial x} = 0, \quad \rho_i|_{t=0} = 0, \quad i = 1, \dots, N. \quad (24)$$

Multiplying (24) by ρ_i , and integrating with respect to x , we arrive at the relations

$$\begin{aligned} \frac{1}{2} \frac{d}{dt} \left(\int_0^1 \rho_i^2 dx \right) &= - \int_0^1 \left(\frac{1}{2} \rho_i^2 \left(\frac{\partial v^{(1)}}{\partial x} \right) + \rho_i^{(2)} \rho_i \left(\frac{\partial v}{\partial x} \right) + \left(\frac{\partial \rho_i^{(2)}}{\partial x} \right) \rho_i v \right) dx \\ &\leq \frac{1}{2} \left(\sup_{[0,1]} \left| \frac{\partial v^{(1)}}{\partial x} \right| \int_0^1 \rho_i^2 dx + \sup_{[0,1]} \rho_i^{(2)} \int_0^1 \left(\rho_i^2 + \left(\frac{\partial v}{\partial x} \right)^2 \right) dx + \right. \\ &\quad \left. + \sup_{[0,1]} v^2 \int_0^1 \left(\frac{\partial \rho_i^{(2)}}{\partial x} \right)^2 dx + \int_0^1 \rho_i^2 dx \right) \leq \\ &\leq C_{10} \left(C_9, \left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, c, m, t^m \right) \left(\int_0^1 \rho_i^2 dx + \sum_{j=1}^N \int_0^1 u_j^2 dx \right). \quad (25) \end{aligned}$$

Here we have used obvious relations

$$\begin{aligned} \sum_{j=1}^N \int_0^1 u_j^2 dx &= \frac{1}{2} \sum_{j=1}^N \sum_{s=1}^m \xi_{js}^2(t), \quad \sup_{[0,1]} v^2 \leq \sum_{i,j=1}^N \sum_{s,l=1}^m |\xi_{il}(t)\xi_{js}(t)|, \\ \int_0^1 \left(\frac{\partial v}{\partial x}\right)^2 dx &= \frac{\pi^2}{2} \sum_{i,j=1}^N \alpha_i \alpha_j \sum_{s=1}^m s^2 \xi_{js}(t) \xi_{is}(t). \end{aligned} \tag{26}$$

From (25), applying the Gronwall inequality and the initial conditions in (24), we obtain the inequalities

$$\int_0^1 \rho_i^2 dx \leq C_{11}(C_{10}, t^m) \sum_{j=1}^N \int_0^t \int_0^1 u_j^2 dx d\tau, \quad i = 1, \dots, N \tag{27}$$

for all $t \in (0, t_m]$. Further, from the equations for $U_i^{(1,2)}$, $i = 1, \dots, N$ (see (14)) due to (20) we get

$$\begin{aligned} &\frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} U_i^2 dx + \sum_{i,j=1}^N \nu_{ij} \int_0^t \int_0^1 \left(\frac{\partial U_i}{\partial x}\right) \left(\frac{\partial U_j}{\partial x}\right) dx d\tau = \\ &= K \sum_{i=1}^N \alpha_i \int_0^t \int_0^1 \rho \left(\frac{\partial U_i}{\partial x}\right) dx d\tau - \sum_{i=1}^N \int_0^t \int_0^1 \rho_i U_i \left(\frac{\partial U_i^{(2)}}{\partial \tau}\right) dx d\tau - \\ &- \sum_{i=1}^N \int_0^t \int_0^1 \rho_i^{(1)} v U_i \left(\frac{\partial U_i^{(2)}}{\partial x}\right) dx d\tau - \sum_{i=1}^N \int_0^t \int_0^1 \rho_i v^{(2)} U_i \left(\frac{\partial U_i^{(2)}}{\partial x}\right) dx d\tau \end{aligned} \tag{28}$$

for all $t \in (0, t_m]$. The first term on the left-hand side of (28) satisfies the estimate

$$\frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} U_i^2 dx \geq \frac{e^{-\pi m^2 c N t^m} \min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}}{2} \sum_{i=1}^N \int_0^1 U_i^2 dx. \tag{29}$$

For the second term on the left-hand side of (28) we have

$$\sum_{i,j=1}^N \int_0^t \int_0^1 \nu_{ij} \left(\frac{\partial U_i}{\partial x}\right) \left(\frac{\partial U_j}{\partial x}\right) dx d\tau \geq C_1 \sum_{i=1}^N \int_0^t \int_0^1 \left(\frac{\partial U_i}{\partial x}\right)^2 dx d\tau. \tag{30}$$

For the first term on the right-hand side of (28) we obtain the relation

$$\begin{aligned} K \sum_{i=1}^N \alpha_i \int_0^t \int_0^1 \rho \left(\frac{\partial U_i}{\partial x} \right) dx d\tau &\leq \frac{C_1}{2} \sum_{i=1}^N \int_0^t \int_0^1 \left(\frac{\partial U_i}{\partial x} \right)^2 dx d\tau + \\ &+ C_{12} (C_1, C_{11}, K, N, t^m) \sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau. \end{aligned} \quad (31)$$

For the second term on the right-hand side of (28) the inequality

$$\begin{aligned} & - \sum_{i=1}^N \int_0^t \int_0^1 \rho_i U_i \left(\frac{\partial U_i^{(2)}}{\partial \tau} \right) dx d\tau \leq \\ & \leq \frac{\varepsilon}{2} \sum_{i=1}^N \sup_{[0,t] \times [0,1]} U_i^2 \int_0^t \int_0^1 \left(\frac{\partial U_i^{(2)}}{\partial \tau} \right)^2 dx d\tau + \frac{C_{11} N t^m}{2\varepsilon} \sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau \leq \\ & \leq \varepsilon m C_8^2 \sum_{i=1}^N \sup_{[0,t]} \int_0^1 U_i^2 dx + \frac{C_{11} N t^m}{2\varepsilon} \sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau \end{aligned}$$

holds, and taking

$$\varepsilon m C_8^2 = \frac{e^{-\pi m^2 c N t^m} \min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}}{4N},$$

we obtain that

$$\begin{aligned} & - \sum_{i=1}^N \int_0^t \int_0^1 \rho_i U_i \left(\frac{\partial U_i^{(2)}}{\partial \tau} \right) dx d\tau \leq \frac{e^{-\pi m^2 c N t^m} \min_{1 \leq i \leq N} \inf_{[0,1]} \rho_{0i}}{4N} \sum_{i=1}^N \sup_{[0,t]} \int_0^1 U_i^2 dx + \\ & + C_{13} \left(C_8, C_{11}, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, c, m, t^m \right) \sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau. \end{aligned} \quad (32)$$

The third term on the right-hand side of (28) can be estimated as follows

$$\begin{aligned} & - \sum_{i=1}^N \int_0^t \int_0^1 \rho_i^{(1)} v U_i \left(\frac{\partial U_i^{(2)}}{\partial x} \right) dx d\tau \leq \\ & \leq C_{14} \left(\sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau + \sum_{i=1}^N \int_0^t \int_0^1 U_i^2 dx d\tau \right), \end{aligned} \quad (33)$$

where $C_{14} = C_{14} \left(\left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, c, m, t^m \right)$. Finally, the last term on the right-hand side of (28) satisfies the relation

$$\begin{aligned}
 - \sum_{i=1}^N \int_0^t \int_0^1 \rho_i v^{(2)} U_i \left(\frac{\partial U_i^{(2)}}{\partial x} \right) dx d\tau &\leq \\
 &\leq C_{15} \left(\sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau + \sum_{i=1}^N \int_0^t \int_0^1 U_i^2 dx d\tau \right), \quad (34)
 \end{aligned}$$

where $C_{15} = C_{15}(C_{11}, N, c, m, t^m)$. Thus, from (28), using (29)–(34), the inequality

$$\sum_{i=1}^N \int_0^1 U_i^2 dx \leq C_{16} \left(\sum_{i=1}^N \int_0^t \int_0^1 u_i^2 dx d\tau + \sum_{i=1}^N \int_0^t \int_0^1 U_i^2 dx d\tau \right)$$

follows, where $C_{16} = C_{16} \left(C_{12}, \dots, C_{15}, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, c, m, t^m \right)$, which, in view of the Gronwall inequality, implies the estimate

$$\sum_{i=1}^N \int_0^1 U_i^2 dx \leq C_{17}(C_{16}, t^m) \sum_{i=1}^N \int_0^{t^m} \int_0^1 u_i^2 dx dt,$$

and, consequently,

$$\|\psi^{(1)} - \psi^{(2)}\|_{(C[0,t^m])^{mN}} \leq C_{18}(C_{17}, t^m) \|\xi^{(1)} - \xi^{(2)}\|_{(C[0,t^m])^{mN}}.$$

The last inequality justifies the continuity of the operator A .

Since the operator A satisfies the assumptions of the Schauder theorem listed above, in V there exists a fixed point ξ of the operator A which, together with the corresponding functions $\rho_i, i = 1, \dots, N$, is a solution to problem (7)–(10). Theorem 2 is proved.

4 Uniform estimates of Galerkin approximations

Let us obtain estimates of solutions to the approximate initial-boundary value problem (7)–(10), which would be uniform with respect to the parameter m and would allow us to pass to the limit as $m \rightarrow \infty$. Let us denote

$$\alpha(t) = \sum_{i=1}^N \int_0^t \int_0^1 \left(\rho_i \left(\frac{\partial u_i}{\partial t} \right)^2 + \left(\frac{\partial^2 u_i}{\partial x^2} \right)^2 \right) dx d\tau, \quad \alpha'(t) \geq 0. \quad (35)$$

Equations (7) imply inequalities (12) which, in turn, imply the estimates

$$C_{19}^{-1} e^{-C_{19}\alpha(t)} \leq \rho_i(x, t) \leq C_{19} e^{C_{19}\alpha(t)}, \quad i = 1, \dots, N, \quad (36)$$

where $C_{19} = C_{19} \left(\left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, T \right)$. We note that (7) imply the equalities

$$\rho_i \frac{\partial^2}{\partial t \partial x} \left(\frac{1}{\rho_i} \right) + \rho_i v \frac{\partial^2}{\partial x^2} \left(\frac{1}{\rho_i} \right) = \frac{\partial^2 v}{\partial x^2}, \quad i = 1, \dots, N, \tag{37}$$

which yield

$$\frac{d}{dt} \left(\int_0^1 \rho_i \left(\frac{\partial}{\partial x} \left(\frac{1}{\rho_i} \right) \right)^2 dx \right) = 2 \int_0^1 \left(\frac{\partial}{\partial x} \left(\frac{1}{\rho_i} \right) \right) \left(\frac{\partial^2 v}{\partial x^2} \right) dx, \tag{38}$$

$i = 1, \dots, N.$

From (38), the relations

$$\begin{aligned} \int_0^1 \rho_i \left(\frac{\partial}{\partial x} \left(\frac{1}{\rho_i} \right) \right)^2 dx &\leq \int_0^1 \rho_{0i} \left(\left(\frac{1}{\rho_{0i}} \right)' \right)^2 dx + \\ &+ \int_0^t \int_0^1 \left(\rho_i \left(\frac{\partial}{\partial x} \left(\frac{1}{\rho_i} \right) \right)^2 + \frac{1}{\rho_i} \left(\frac{\partial^2 v}{\partial x^2} \right)^2 \right) dx d\tau, \quad i = 1, \dots, N \end{aligned} \tag{39}$$

follow.

Remark 1. *In order to obtain (39), we need (in (37), (38)) an additional smoothness of $\rho_i, i = 1, \dots, N$ in comparison with (11), however the formulation of relations (39) does not require any additional regularity. This means that (39) can be obtained via regularization of $\rho_{0i}, i = 1, \dots, N$, derivation of (39) for the solutions of the corresponding problems, and then the limit via the regularization parameter. The derivation of relations (23) should be understood in a similar way.*

Using (35), (36) and the Gronwall inequality, from (39) we obtain the estimates

$$\int_0^1 \left(\frac{\partial}{\partial x} \left(\frac{1}{\rho_i} \right) \right)^2 dx + \int_0^1 \left(\frac{\partial \rho_i}{\partial x} \right)^2 dx \leq C_{20} e^{C_{20}\alpha(t)}, \quad i = 1, \dots, N, \tag{40}$$

where $C_{20} = C_{20} \left(C_{19}, \left\{ \|\rho_{0i}\|_{W_2^1(0,1)} \right\}_{i=1}^N, \left\{ \inf_{[0,1]} \rho_{0i} \right\}_{i=1}^N, N, T \right)$. Further, multiplying (8) by $\psi'_{ik} + \pi^2 k^2 \psi_{ik}$, summarizing with respect to i, k , and taking into account (7), (10), we obtain the relation (here, we also use the symmetry of the matrix \mathbf{N})

$$\sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial u_i}{\partial t} \right)^2 dx + \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial^2 u_i}{\partial x^2} \right) \left(\frac{\partial^2 u_j}{\partial x^2} \right) dx +$$

$$\begin{aligned}
 & + \frac{1}{2} \frac{d}{dt} \left(\sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial u_i}{\partial x} \right)^2 dx \right) + \frac{1}{2} \frac{d}{dt} \left(\sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx \right) = \\
 & = - \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial u_i}{\partial t} \right) \left(\frac{\partial u_i}{\partial x} \right) dx - K \int_0^1 \left(\frac{\partial \rho}{\partial x} \right) \left(\frac{\partial v}{\partial t} \right) dx + \\
 & + K \int_0^1 \left(\frac{\partial \rho}{\partial x} \right) \left(\frac{\partial^2 v}{\partial x^2} \right) dx - \sum_{i=1}^N \int_0^1 \left(\frac{\partial \rho_i}{\partial x} \right) \left(\frac{\partial u_i}{\partial t} \right) \left(\frac{\partial u_i}{\partial x} \right) dx + \\
 & + 2 \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial^2 u_i}{\partial x^2} \right) dx. \quad (41)
 \end{aligned}$$

The left-hand side of (41) satisfies the estimate (since $\mathbf{N} > 0$)

$$\begin{aligned}
 & \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial u_i}{\partial t} \right)^2 dx + \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial^2 u_i}{\partial x^2} \right) \left(\frac{\partial^2 u_j}{\partial x^2} \right) dx + \\
 & + \frac{1}{2} \frac{d}{dt} \left(\sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial u_i}{\partial x} \right)^2 dx \right) + \frac{1}{2} \frac{d}{dt} \left(\sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx \right) \geq \\
 & \geq C_{21}(C_1)\alpha'(t) + \beta'(t), \quad (42)
 \end{aligned}$$

where

$$\beta(t) = \frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i \left(\frac{\partial u_i}{\partial x} \right)^2 dx + \frac{1}{2} \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx.$$

We separately consider each term on the right-hand side of (41). For the first term on the right-hand side of (41) we have

$$\begin{aligned}
 & - \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial u_i}{\partial t} \right) \left(\frac{\partial u_i}{\partial x} \right) dx \leq \\
 & \leq \sum_{i=1}^N \sup_{[0,1]} |v| \left(\int_0^1 \rho_i \left(\frac{\partial u_i}{\partial t} \right)^2 dx \right)^{1/2} \left(\int_0^1 \rho_i \left(\frac{\partial u_i}{\partial x} \right)^2 dx \right)^{1/2} \leq \\
 & \leq \frac{C_{21}}{10} \alpha'(t) + C_{22} \beta^2(t) e^{C_{22}\alpha(t)}, \quad (43)
 \end{aligned}$$

where $C_{22} = C_{22}(C_{19}, C_{21}, N)$. For the second and third terms on the right-hand side of (41) we obtain

$$-K \int_0^1 \left(\frac{\partial \rho}{\partial x} \right) \left(\frac{\partial v}{\partial t} \right) dx \leq \frac{C_{21}}{10} \alpha'(t) + C_{23} e^{C_{23}\alpha(t)}, \quad (44)$$

$$K \int_0^1 \left(\frac{\partial \rho}{\partial x} \right) \left(\frac{\partial^2 v}{\partial x^2} \right) dx \leq \frac{C_{21}}{10} \alpha'(t) + C_{24} e^{C_{24}\alpha(t)} \quad (45)$$

respectively, where $C_{23} = C_{23}(C_{19}, C_{20}, C_{21}, K, N)$, $C_{24} = C_{24}(C_{20}, C_{21}, K, N)$. For the fourth term on the right-hand side of (41), using the interpolation estimate

$$\sup_{[0,1]} \left| \frac{\partial u_i}{\partial x} \right| \leq \sqrt{2} \left(\int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx \right)^{1/2} \left(\int_0^1 \left(\frac{\partial^2 u_i}{\partial x^2} \right)^2 dx \right)^{1/2},$$

we deduce

$$\begin{aligned} & - \sum_{i=1}^N \int_0^1 \left(\frac{\partial \rho_i}{\partial x} \right) \left(\frac{\partial u_i}{\partial t} \right) \left(\frac{\partial u_i}{\partial x} \right) dx \leq \\ & \leq \sum_{i=1}^N \sup_{[0,1]} \left| \frac{\partial u_i}{\partial x} \right| \left(\int_0^1 \frac{1}{\rho_i} \left(\frac{\partial \rho_i}{\partial x} \right)^2 dx \right)^{1/2} \left(\int_0^1 \rho_i \left(\frac{\partial u_i}{\partial t} \right)^2 dx \right)^{1/2} \leq \\ & \leq \frac{C_{21}}{10} \alpha'(t) + C_{25} \beta(t) e^{C_{25}\alpha(t)}, \quad C_{25} = C_{25}(C_{19}, C_{20}, C_{21}, N). \quad (46) \end{aligned}$$

Finally, for the last term on the right-hand side of (41) we obtain the relation

$$\begin{aligned} & 2 \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial^2 u_i}{\partial x^2} \right) dx \leq \\ & \leq 2 \sum_{i=1}^N \sup_{[0,1]} |v| \sup_{[0,1]} \sqrt{\rho_i} \left(\int_0^1 \rho_i \left(\frac{\partial u_i}{\partial x} \right)^2 dx \right)^{1/2} \left(\int_0^1 \left(\frac{\partial^2 u_i}{\partial x^2} \right)^2 dx \right)^{1/2} \leq \\ & \leq \frac{C_{21}}{10} \alpha'(t) + C_{26} \beta^2(t) e^{C_{26}\alpha(t)}, \quad C_{26} = C_{26}(C_{19}, C_{21}, N). \quad (47) \end{aligned}$$

Thus, from (43)–(46) it follows that the right-hand side of (41)

$$- \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial u_i}{\partial t} \right) \left(\frac{\partial u_i}{\partial x} \right) dx - K \int_0^1 \left(\frac{\partial \rho}{\partial x} \right) \left(\frac{\partial v}{\partial t} \right) dx +$$

$$\begin{aligned}
 & + K \int_0^1 \left(\frac{\partial \rho}{\partial x} \right) \left(\frac{\partial^2 v}{\partial x^2} \right) dx - \sum_{i=1}^N \int_0^1 \left(\frac{\partial \rho_i}{\partial x} \right) \left(\frac{\partial u_i}{\partial t} \right) \left(\frac{\partial u_i}{\partial x} \right) dx + \\
 & \quad + 2 \sum_{i=1}^N \int_0^1 \rho_i v \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial^2 u_i}{\partial x^2} \right) dx \leq \\
 & \leq \frac{C_{21}}{2} \alpha'(t) + C_{27} (1 + \beta^2(t)) e^{C_{27} \alpha(t)}, \quad C_{27} = C_{27}(C_{22}, \dots, C_{26}). \quad (48)
 \end{aligned}$$

Combining relations (42) and (48), from (41) we obtain the inequality

$$\left(\frac{C_{21}}{2} \alpha(t) + \beta(t) \right)' \leq C_{28} e^{C_{28} \left(C_{21} \frac{\alpha(t)}{2} + \beta(t) \right)}, \quad C_{28} = C_{28}(C_{21}, C_{27}). \quad (49)$$

We take any $C_{29} > \beta(0)$, for example, $C_{29} = 2\beta(0)$. Then for

$$t_0 = \min \left(T, \frac{e^{-C_{28}\beta(0)} - e^{-C_{28}C_{29}}}{C_{28}^2} \right) \quad (50)$$

we derive from (49) that the estimate

$$\sup_{0 \leq t \leq t_0} (\alpha + \beta) \leq \left(1 + \frac{2}{C_{21}} \right) C_{30}, \quad C_{30} = \frac{1}{C_{28}} \ln \left(\frac{1}{e^{-C_{28}\beta(0)} - C_{28}^2 t_0} \right)$$

holds, which together with (7), (36) and (40) yields that

$$\begin{aligned}
 & \sum_{i=1}^N \left(\|\rho_i\|_{L_\infty(0, t_0; W_2^1(0, 1))} + \|u_i\|_{L_\infty(0, t_0; W_2^1(0, 1))} + \|u_i\|_{L_2(0, t_0; W_2^2(0, 1))} + \right. \\
 & \quad \left. + \left\| \frac{\partial \rho_i}{\partial t} \right\|_{L_\infty(0, t_0; L_2(0, 1))} + \left\| \frac{\partial u_i}{\partial t} \right\|_{L_2(Q_{t_0})} + \left\| \frac{1}{\rho_i} \right\|_{L_\infty(Q_{t_0})} \right) \leq C_{31}, \quad (51)
 \end{aligned}$$

where $Q_{t_0} = (0, t_0) \times (0, 1)$, $C_{31} = C_{31}(C_{19}, C_{20}, C_{21}, C_{30}, N)$.

5 Convergence of Galerkin approximations

We have constructed the solutions $(\rho_1^m, \dots, \rho_N^m, u_1^m, \dots, u_N^m)$ to problems (7)–(10) for all $m \in \mathbb{N}$, and now extend them, if necessary, for $(0, t_0)$, and we can use estimate (51) for them. Based on this estimate, we can extract a subsequence from the mentioned sequence (keeping the same notation, below this procedure is implied as necessary) such that

$$\rho_i^m \rightarrow \rho_i \text{ weakly* in } L_\infty(0, t_0; W_2^1(0, 1)),$$

$u_i^m \rightarrow u_i$ weakly* in $L_\infty(0, t_0; W_2^1(0, 1))$ and weakly in $L_2(0, t_0; W_2^2(0, 1))$ as $m \rightarrow \infty$ for all $i = 1, \dots, N$. The other properties listed in (5) are also satisfied by this sequence in Q_{t_0} uniformly with respect to m . Consequently, the limit functions belong to the corresponding classes. We show that $(\rho_1, \dots, \rho_N, u_1, \dots, u_N)$ is a strong solution to problem (1)–(4) on $(0, t_0)$.

By the Arzela–Ascoli theorem (see [54, Theorem 1.70, P. 58]) and the uniform estimates for ρ_i^m, u_i^m in $L_\infty(0, t_0; W_2^1(0, 1))$ and for $\frac{\partial \rho_i^m}{\partial t}, \frac{\partial u_i^m}{\partial t}$ in $L_2(Q_{t_0})$ (cf. (51)) we have

$$\rho_i^m \rightarrow \rho_i \text{ as } m \rightarrow \infty \text{ strongly in } C([0, t_0]; L_2(0, 1)), \quad i = 1, \dots, N, \quad (52)$$

$$u_i^m \rightarrow u_i \text{ as } m \rightarrow \infty \text{ strongly in } C([0, t_0]; L_2(0, 1)), \quad i = 1, \dots, N. \quad (53)$$

Since $\frac{\partial u_i^m}{\partial t}$ are bounded in $L_2(Q_{t_0})$, an uniform estimate for $\frac{\partial^2 u_i^m}{\partial t \partial x}$ in $L_2(0, t_0; W_2^{-1}(0, 1))$ is valid, which, together with the estimate for $\frac{\partial u_i^m}{\partial x}$ in $L_2(0, t_0; W_2^1(0, 1))$ means via Lions–Aubin’s lemma (see [54, Theorem 1.71, P. 59]) that

$$\frac{\partial u_i^m}{\partial x} \rightarrow \frac{\partial u_i}{\partial x} \text{ as } m \rightarrow \infty \text{ strongly in } L_2(Q_{t_0}), \quad i = 1, \dots, N. \quad (54)$$

Hence (53) leads to the relations

$$u_i^m \rightarrow u_i \text{ as } m \rightarrow \infty \text{ strongly in } L_2(0, t_0; C[0, 1]), \quad i = 1, \dots, N. \quad (55)$$

Thus, the limit functions $\rho_i, u_i, i = 1, \dots, N$, satisfy (almost everywhere in Q_{t_0}) the continuity equations (1), in which $v = \sum_{j=1}^N \alpha_j u_j$, the initial data (3) for almost all $x \in (0, 1)$ and the boundary conditions (4) for almost all $t \in (0, t_0)$.

The boundedness of $\frac{\partial u_i^m}{\partial t}$ in $L_2(Q_{t_0})$ implies the weak convergence of $\frac{\partial u_i^m}{\partial t}$ to $\frac{\partial u_i}{\partial t}$ in $L_2(Q_{t_0})$, which, together with (52) and the boundedness of $\rho_i^m \frac{\partial u_i^m}{\partial t}$ in $L_2(Q_{t_0})$ implies

$$\rho_i^m \frac{\partial u_i^m}{\partial t} \rightarrow \rho_i \frac{\partial u_i}{\partial t} \text{ as } m \rightarrow \infty \text{ weakly in } L_2(Q_{t_0}), \quad i = 1, \dots, N.$$

Further, from (52) and (54) it follows that

$$\rho_i^m \frac{\partial u_i^m}{\partial x} \rightarrow \rho_i \frac{\partial u_i}{\partial x} \text{ as } m \rightarrow \infty \text{ strongly in } L_2(0, t_0; L_1(0, 1)), \quad i = 1, \dots, N,$$

and hence (55) yields that the convergences

$$\left(\rho_i^m \frac{\partial u_i^m}{\partial x} \right) u_j^m \rightarrow \left(\rho_i \frac{\partial u_i}{\partial x} \right) u_j \text{ as } m \rightarrow \infty \text{ strongly in } L_1(Q_{t_0}) \quad (56)$$

are valid for all $i, j = 1, \dots, N$.

By (8), for any functions of the form ($i = 1, \dots, N$)

$$\varphi_i = \sum_{k=1}^M \eta_{ik}(t) \sin(\pi k x), \quad \eta_{ik} \in C[0, t_0], \quad k = 1, \dots, M, \quad M \leq m, \quad (57)$$

we have the equalities

$$\int_0^{t_0} \int_0^1 \left(\rho_i^m \frac{\partial u_i^m}{\partial t} + \rho_i^m v^m \frac{\partial u_i^m}{\partial x} + \alpha_i K \frac{\partial \rho^m}{\partial x} - \sum_{j=1}^N \nu_{ij} \frac{\partial^2 u_j^m}{\partial x^2} \right) \varphi_i dx dt = 0,$$

$$i = 1, \dots, N,$$

passing in which to the limit as $m \rightarrow \infty$ (by the proved convergences), we find (since the set of functions φ_i , $i = 1, \dots, N$ of form (57) is everywhere dense in $L_2(Q_{t_0})$) that the momentum equations (2) hold for the limit functions

$$\rho_i, u_i, i = 1, \dots, N \text{ almost everywhere } Q_{t_0}, \text{ with } \rho = \sum_{i=1}^N \rho_i.$$

Thus, we have proved the existence of a solution to the initial-boundary value problem (1)–(4) in small time. In order to continue the local solution defined on the interval $(0, t_0)$ into the entire target interval $(0, T)$, it is necessary to obtain a priori estimates for this local solution which contain constants depending on the input data of the problem and on the value T , but not on the parameter t_0 (see, for example, [21, P. 40]).

6 Global a priori estimates

During the further study of the unique solvability of problem (1)–(4), the use of the Lagrangian mass coordinates is convenient. Let us accept t and $y(t, x) = \int_0^x \rho(t, s) ds$ as new independent variables. Then system (1), (2) takes the form

$$\frac{\partial \tilde{\rho}_i}{\partial t} + \tilde{\rho}_i \frac{\partial \tilde{v}}{\partial y} = 0, \quad i = 1, \dots, N, \quad \tilde{v} = \sum_{j=1}^N \alpha_j \tilde{u}_j, \quad (58)$$

$$\frac{\tilde{\rho}_i}{\tilde{\rho}} \frac{\partial \tilde{u}_i}{\partial t} + \alpha_i K \frac{\partial \tilde{\rho}}{\partial y} = \sum_{j=1}^N \nu_{ij} \frac{\partial}{\partial y} \left(\tilde{\rho} \frac{\partial \tilde{u}_j}{\partial y} \right), \quad i = 1, \dots, N, \quad \tilde{\rho} = \sum_{j=1}^N \tilde{\rho}_j. \quad (59)$$

The domain Q_T is transformed into the rectangular $\Pi_T = (0, T) \times (0, d)$, where $d = \int_0^1 \rho_0 dx > 0$, $\rho_0 = \sum_{j=1}^N \rho_{0j}$, and the initial and boundary conditions take the form

$$\tilde{\rho}_i|_{t=0} = \tilde{\rho}_{0i}(y), \quad \tilde{u}_i|_{t=0} = \tilde{u}_{0i}(y), \quad y \in [0, d], \quad i = 1, \dots, N, \quad (60)$$

$$\tilde{u}_i|_{y=0} = \tilde{u}_i|_{y=d} = 0, \quad t \in [0, T], \quad i = 1, \dots, N. \quad (61)$$

Let us construct a priori estimates. First of all, we note that the summation of (58) with respect to i gives

$$\frac{\partial \tilde{\rho}}{\partial t} + \tilde{\rho}^2 \frac{\partial \tilde{v}}{\partial y} = 0, \quad (62)$$

and hence

$$\frac{\partial}{\partial t} \left(\frac{\tilde{\rho}_i}{\tilde{\rho}} \right) = 0, \quad i = 1, \dots, N.$$

Hence, due to (60) we get the equalities

$$\frac{\tilde{\rho}_i(t, y)}{\tilde{\rho}(t, y)} = \frac{\tilde{\rho}_{0i}(y)}{\tilde{\rho}_0(y)} \quad \text{as } (t, y) \in [0, T] \times [0, d] \quad (63)$$

for all $i = 1, \dots, N$, where $\tilde{\rho}_0 = \sum_{j=1}^N \tilde{\rho}_{0j}$. In the Eulerian coordinates the ratios ρ_i/ρ , $i = 1, \dots, N$, satisfy the transport equations, and we only have the inequalities

$$0 < \inf_{[0,1]} \frac{\rho_{0i}}{\rho_0} \leq \frac{\rho_i(t, x)}{\rho(t, x)} \leq \sup_{[0,1]} \frac{\rho_{0i}}{\rho_0} \leq 1 \quad \text{for } (t, x) \in [0, T] \times [0, 1]. \quad (64)$$

Let us multiply equations (2) by u_i , integrate over x and sum with respect to i . In view of (1), (4) and the condition $\mathbf{N} > 0$, the following relations hold

$$\begin{aligned} \sum_{i=1}^N \int_0^1 \left(\rho_i \frac{\partial u_i}{\partial t} + \rho_i v \frac{\partial u_i}{\partial x} \right) u_i dx &= \frac{1}{2} \frac{d}{dt} \left(\sum_{i=1}^N \int_0^1 \rho_i u_i^2 dx \right), \\ \sum_{i=1}^N \alpha_i K \int_0^1 u_i \frac{\partial \rho}{\partial x} dx &= -K \int_0^1 \rho \frac{\partial v}{\partial x} dx = K \frac{d}{dt} \int_0^1 (\rho \ln \rho - (\ln d + 1)\rho + d) dx, \\ \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial^2 u_j}{\partial x^2} \right) u_i dx &= - \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx \leq \\ &\leq -C_1 \sum_{i=1}^N \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx, \end{aligned} \quad (65)$$

and hence we get the inequality

$$\begin{aligned} \frac{d}{dt} \int_0^1 \left(\frac{1}{2} \sum_{i=1}^N \rho_i u_i^2 + K (\rho \ln \rho - (\ln d + 1)\rho + d) \right) dx + \\ + C_1 \sum_{i=1}^N \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx \leq 0. \end{aligned} \quad (66)$$

Integrating (66) with respect to t , and using (3), we obtain the bound

$$\int_0^1 \left(\frac{1}{2} \sum_{i=1}^N \rho_i u_i^2 + K (\rho \ln \rho - (\ln d + 1)\rho + d) \right) dx + C_1 \sum_{i=1}^N \int_0^t \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx d\tau$$

$$\leq \int_0^1 \left(\frac{1}{2} \sum_{i=1}^N \rho_{0i} u_{0i}^2 + K(\rho_0 \ln \rho_0 - (\ln d + 1)\rho_0 + d) \right) dx,$$

which, due to (64), implies the estimate

$$\begin{aligned} \sum_{i=1}^N \int_0^1 \rho u_i^2 dx + \int_0^1 (\rho \ln \rho - (\ln d + 1)\rho + d) dx + \\ + \sum_{i=1}^N \int_0^T \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx dt \leq C_{32}, \end{aligned} \quad (67)$$

where $C_{32} = C_{32}(C_1, \left\{ \inf_{[0,1]} \frac{\rho_{0i}}{\rho_0} \right\}_{i=1}^N, \left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, \{ \|u_{0i}\|_{L_2(0,1)} \}_{i=1}^N, K, N, d)$. Let us rewrite (67), using the Lagrangian mass coordinates, in the form

$$\begin{aligned} \sum_{i=1}^N \int_0^d \tilde{u}_i^2 dy + \int_0^d \frac{\tilde{\rho} \ln \tilde{\rho} - (\ln d + 1)\tilde{\rho} + d}{\tilde{\rho}} dy + \\ + \sum_{i=1}^N \int_0^T \int_0^d \tilde{\rho} \left(\frac{\partial \tilde{u}_i}{\partial y} \right)^2 dy dt \leq C_{32}. \end{aligned} \quad (68)$$

Let us note that, from estimates (67), in view of (4), the inequality

$$\sum_{i=1}^N \int_0^T \left(\sup_{[0,1]} |u_i| \right)^2 dt \leq C_{32} \quad (69)$$

obviously follows.

Let us rewrite equations (2), using (1), in the form

$$\begin{aligned} \sum_{j=1}^N \tilde{\nu}_{ij} \left(\frac{\partial(\rho_j u_j)}{\partial t} + \frac{\partial(\rho_j v u_j)}{\partial x} \right) + K \left(\sum_{j=1}^N \tilde{\nu}_{ij} \alpha_j \right) \frac{\partial \rho}{\partial x} = \frac{\partial^2 u_i}{\partial x^2}, \quad (70) \\ i = 1, \dots, N, \end{aligned}$$

where $\tilde{\nu}_{ij}$ are the entries of the symmetric matrix $\tilde{\mathbf{N}} = \mathbf{N}^{-1} > 0$. We multiply (70) by α_i and sum with respect to i , and we obtain

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial x} \left(\frac{\partial v}{\partial x} - \tilde{K} \rho - vV \right), \quad (71)$$

where $V = \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \rho_j u_j$, $\tilde{K} = K \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \alpha_j > 0$. We denote

$$\gamma(t, x) = \int_0^t \left(\frac{\partial v}{\partial x} - \tilde{K} \rho - vV \right) d\tau + \int_0^x V_0 ds, \quad (72)$$

where $V_0(x) = V(0, x) = \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \rho_{0j} u_{0j}$. In view of (67), we have

$$\begin{aligned} \sup_{[0,T]} \int_0^1 \left| \frac{\partial \gamma}{\partial x} \right| dx &= \sup_{[0,T]} \int_0^1 |V| dx \leq C_{33}(C_{32}, \mathbf{N}, N, d), \\ \sup_{[0,T]} \left| \int_0^1 \gamma dx \right| &\leq C_{34} \left(C_{32}, \{ \|\rho_{0i} u_{0i}\|_{L_1(0,1)} \}_{i=1}^N, \tilde{\mathbf{N}}, \tilde{K}, N, T, d \right), \end{aligned}$$

and hence, using Poincaré's inequality (see [54, Lemma 1.43, P. 44]), we get

$$\sup_{[0,T]} \int_0^1 |\gamma| dx \leq C_{35}(C_{33}, C_{34}),$$

and we arrive at the boundedness of γ in $L_\infty(0, T; W_1^1(0, 1))$. Using this and the fact $W_1^1(0, 1) \hookrightarrow L_\infty(0, 1)$, we obtain the estimate

$$\|\gamma\|_{L_\infty(Q_T)} \leq C_{36}(C_{33}, C_{35}).$$

Let us note that, in view of (1), (71) and (72), the following relations hold

$$\frac{\partial(\rho e^\gamma)}{\partial t} + v \frac{\partial(\rho e^\gamma)}{\partial x} = -\tilde{K} e^\gamma \rho^2 \leq 0,$$

and hence

$$\rho(t, x) e^{\gamma(t, x)} \leq \left(\sup_{[0,1]} \rho_0 \right) e^{\int_0^1 |V_0| dx},$$

so that the estimate

$$\rho(t, x) \leq C_{37} \quad \text{as } (t, x) \in [0, T] \times [0, 1] \quad (73)$$

is valid, where $C_{37} = C_{37} \left(C_{36}, \left\{ \sup_{[0,1]} \rho_{0i} \right\}_{i=1}^N, \{ \|\rho_{0i} u_{0i}\|_{L_1(0,1)} \}_{i=1}^N, \tilde{\mathbf{N}}, N \right)$.

Let us use equations (1), (2) in the form (58), (59). We rewrite equations (59) as

$$\sum_{j=1}^N \tilde{\nu}_{ij} \frac{\tilde{\rho}_j}{\tilde{\rho}} \frac{\partial \tilde{u}_j}{\partial t} + K \left(\sum_{j=1}^N \tilde{\nu}_{ij} \alpha_j \right) \frac{\partial \tilde{\rho}}{\partial y} = \frac{\partial}{\partial y} \left(\tilde{\rho} \frac{\partial \tilde{u}_i}{\partial y} \right), \quad i = 1, \dots, N, \quad (74)$$

and then multiply (74) by α_i and sum with respect to i . In view of (63), we obtain

$$\sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \frac{\partial \tilde{u}_j}{\partial t} + \tilde{K} \frac{\partial \tilde{\rho}}{\partial y} = \frac{\partial}{\partial y} \left(\tilde{\rho} \frac{\partial \tilde{v}}{\partial y} \right). \quad (75)$$

We extract from (62) that

$$\tilde{\rho} \frac{\partial \tilde{v}}{\partial y} = - \frac{\partial \ln \tilde{\rho}}{\partial t} \quad (76)$$

and substitute this into (75), then we get

$$\frac{\partial^2 \ln \tilde{\rho}}{\partial t \partial y} + \tilde{K} \frac{\partial \tilde{\rho}}{\partial y} = - \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \frac{\partial \tilde{u}_j}{\partial t}.$$

We multiply this equality by $\frac{\partial \ln \tilde{\rho}}{\partial y}$ and integrate with respect to y , then we obtain the relation

$$\begin{aligned} \frac{1}{2} \frac{d}{dt} \left(\int_0^d \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right)^2 dy \right) + \tilde{K} \int_0^d \tilde{\rho} \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right)^2 dy = \\ = - \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \frac{\partial \tilde{u}_j}{\partial t} \right) \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right) dy. \end{aligned} \quad (77)$$

Let us transform the right-hand side of (77) via the integration by parts and using (76):

$$\begin{aligned} - \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \frac{\partial \tilde{u}_j}{\partial t} \right) \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right) dy = \\ = - \frac{d}{dt} \left(\sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} u_j \right) \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right) dy \right) + \\ + \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \right)' \tilde{\rho} \tilde{u}_j \left(\frac{\partial \tilde{v}}{\partial y} \right) dy + \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \frac{\tilde{\rho}_{0j} \tilde{\rho}}{\tilde{\rho}_0} \left(\frac{\partial \tilde{u}_j}{\partial y} \right) \left(\frac{\partial \tilde{v}}{\partial y} \right) dy. \end{aligned} \quad (78)$$

Thus, after integration of (77) with respect to t , taking into account (73) and (78), we get

$$\int_0^d \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right)^2 dy + 2\tilde{K} \int_0^t \int_0^d \tilde{\rho} \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right)^2 dy d\tau \leq \int_0^d ((\ln \tilde{\rho}_0)')^2 dy -$$

$$\begin{aligned}
 & -2 \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} u_j \right) \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right) dy + 2 \sum_{i,j=1}^N \tilde{\nu}_{ij} \alpha_i \int_0^d \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \tilde{u}_{0j} \right) (\ln \tilde{\rho}_0)' dy + \\
 & + 2\sqrt{C_{37}} \sum_{i,j=1}^N |\tilde{\nu}_{ij}| \int_0^t \left\| \left(\frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \right)' \right\|_{L_2(0,d)} \|\tilde{u}_j\|_{L_\infty(0,d)} \left\| \sqrt{\tilde{\rho}} \frac{\partial \tilde{v}}{\partial y} \right\|_{L_2(0,d)} d\tau + \\
 & + 2 \sum_{i,j=1}^N |\tilde{\nu}_{ij}| \sup_{[0,d]} \frac{\tilde{\rho}_{0j}}{\tilde{\rho}_0} \int_0^t \left\| \tilde{\rho} \left(\frac{\partial \tilde{u}_j}{\partial y} \right) \left(\frac{\partial \tilde{v}}{\partial y} \right) \right\|_{L_1(0,d)} d\tau.
 \end{aligned}$$

Using estimates (68), (69) and (73), we derive from this the inequality

$$\int_0^d \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right)^2 dy + \int_0^T \int_0^d \tilde{\rho} \left(\frac{\partial \ln \tilde{\rho}}{\partial y} \right)^2 dy dt \leq C_{38}, \tag{79}$$

where $C_{38} = C_{38} \left(C_{32}, C_{37}, \left\{ \left\| \frac{\tilde{\rho}_{0i}}{\tilde{\rho}_0} \right\|_{W_2^1(0,d)} \right\}_{i=1}^N, \|(\ln \tilde{\rho}_0)'\|_{L_2(0,d)}, \tilde{K}, \tilde{N}, N, \left\{ \|\tilde{u}_{0i}\|_{L_2(0,d)} \right\}_{i=1}^N \right)$.

From (60)–(62) it follows obviously that for any $t \in [0, T]$ there exists a point $\delta(t) \in [0, d]$ such that

$$\tilde{\rho}(t, \delta(t)) = d. \tag{80}$$

Hence, we can use the representation

$$\ln \tilde{\rho}(t, y) = \ln \tilde{\rho}(t, \delta(t)) + \int_{\delta(t)}^y \frac{\partial \ln \tilde{\rho}(t, s)}{\partial s} ds,$$

from which, via Hölder’s inequality, and using (79) and (80), we get

$$|\ln \tilde{\rho}(t, y)| \leq |\ln d| + \sqrt{d} \left\| \frac{\partial \ln \tilde{\rho}}{\partial y} \right\|_{L_2(0,d)} \leq C_{39}(C_{38}, d).$$

This leads immediately to

$$\tilde{\rho}(t, y) \geq C_{40}(C_{39}) \quad \text{as } (t, y) \in [0, T] \times [0, d]. \tag{81}$$

From (63), (73) and (81) we obtain that for all $i = 1, \dots, N$

$$C_{41} \leq \tilde{\rho}_i(t, y) \leq C_{37} \quad \text{as } (t, y) \in [0, T] \times [0, d], \tag{82}$$

where $C_{41} = C_{41} \left(C_{40}, \left\{ \inf_{[0,d]} \frac{\tilde{\rho}_{0i}}{\tilde{\rho}_0} \right\}_{i=1}^N \right)$. Hence, for all $i = 1, \dots, N$ we have

$$C_{41} \leq \rho_i(t, x) \leq C_{37} \quad \text{as } (t, x) \in [0, T] \times [0, 1]. \tag{83}$$

From (63), (73) and (79) now it follows that

$$\int_0^1 \left(\frac{\partial \rho_i}{\partial x} \right)^2 dx \leq C_{42}, \quad i = 1, \dots, N, \quad (84)$$

where $C_{42} = C_{42} \left(C_{37}, C_{38}, \left\{ \sup_{[0,d]} \frac{\tilde{\rho}_{0i}}{\tilde{\rho}_0} \right\}_{i=1}^N, \left\{ \left\| \left(\frac{\tilde{\rho}_0}{\tilde{\rho}_{0i}} \right)' \right\|_{L_2(0,d)} \right\}_{i=1}^N \right)$, and hence

$$\int_0^1 \left(\frac{\partial \rho}{\partial x} \right)^2 dx \leq C_{43}(C_{42}, N). \quad (85)$$

We square equations (2), divide by ρ_i and sum the result with respect to i , then we get

$$\begin{aligned} \sum_{i=1}^N \rho_i \left(\frac{\partial u_i}{\partial t} \right)^2 + \sum_{i=1}^N \frac{1}{\rho_i} \left(\sum_{j=1}^N \nu_{ij} \frac{\partial^2 u_j}{\partial x^2} \right)^2 - 2 \sum_{i=1}^N \left(\frac{\partial u_i}{\partial t} \right) \left(\sum_{j=1}^N \nu_{ij} \frac{\partial^2 u_j}{\partial x^2} \right) = \\ = \sum_{i=1}^N \rho_i \left(v \frac{\partial u_i}{\partial x} + \frac{\alpha_i K}{\rho_i} \frac{\partial \rho}{\partial x} \right)^2. \end{aligned} \quad (86)$$

Let us introduce the function $\theta(t)$ via the relation:

$$\begin{aligned} \theta(t) = \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx + \\ + \sum_{i=1}^N \int_0^t \int_0^1 \left(\rho_i \left(\frac{\partial u_i}{\partial \tau} \right)^2 + \frac{1}{\rho_i} \left(\sum_{j=1}^N \nu_{ij} \frac{\partial^2 u_j}{\partial x^2} \right)^2 \right) dx d\tau. \end{aligned}$$

Then (86) and inequalities (65), (83) and (85) give the estimate (here the symmetry of the matrix \mathbf{N} is used)

$$\begin{aligned} \theta'(t) \leq C_{44} + C_{45} \left(\sum_{j=1}^N \|u_j\|_{L_\infty(0,1)}^2 \right) \left(\sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx \right) \leq \\ \leq C_{44} + C_{45} \left(\sum_{j=1}^N \|u_j\|_{L_\infty(0,1)}^2 \right) \theta(t), \end{aligned}$$

where $C_{44} = C_{44}(C_{41}, C_{43}, K, N)$, $C_{16} = C_{16}(C_1, C_{37}, N)$, from which, via Gronwall's lemma (see also (69)), it follows that

$$\theta(t) \leq C_{46} (C_{32}, C_{44}, C_{45}, \{\|u'_{0i}\|_{L_2(0,1)}\}_{i=1}^N, \mathbf{N}, N, T). \quad (87)$$

It follows immediately from (87) that

$$\begin{aligned} \sum_{i=1}^N \left(\int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx + \int_0^T \int_0^1 \left(\frac{\partial u_i}{\partial t} \right)^2 dx dt + \int_0^T \int_0^1 \left(\frac{\partial^2 u_i}{\partial x^2} \right)^2 dx dt \right) \leq \\ \leq C_{47}(C_1, C_{37}, C_{41}, C_{46}, N). \end{aligned} \quad (88)$$

Finally, from the continuity equations (1) and the estimates (83), (84) and (88) we obtain that

$$\int_0^1 \left(\frac{\partial \rho_i}{\partial t} \right)^2 dx \leq C_{48}(C_{37}, C_{42}, C_{47}, N), \quad i = 1, \dots, N.$$

Thereby, we have obtained all estimates which are necessary (and sufficient) to continue the local solution to the initial-boundary value problem (1)–(4) from the interval $(0, t_0)$ into the entire target interval $(0, T)$. In order to conclude the proof of Theorem 1 we need to justify the uniqueness of the solution to the initial-boundary value problem (1)–(4).

7 Uniqueness of the solution

We assume that $(\rho_1^{(1)}, \dots, \rho_N^{(1)}, u_1^{(1)}, \dots, u_N^{(1)})$ and $(\rho_1^{(2)}, \dots, \rho_N^{(2)}, u_1^{(2)}, \dots, u_N^{(2)})$ are two solutions to the initial-boundary value problem (1)–(4), and let $v^{(1,2)} = \sum_{j=1}^N \alpha_j u_j^{(1,2)}$, $\rho^{(1,2)} = \sum_{j=1}^N \rho_j^{(1,2)}$. We set $\rho_i = \rho_i^{(1)} - \rho_i^{(2)}$, $u_i = u_i^{(1)} - u_i^{(2)}$, $i = 1, \dots, N$, $v = v^{(1)} - v^{(2)}$, $\rho = \rho^{(1)} - \rho^{(2)}$.

From (1), (3) we have (see (24))

$$\frac{\partial \rho_i}{\partial t} + \partial_x (\rho_i v^{(1)}) + \partial_x (\rho_i^{(2)} v) = 0, \quad \rho_i|_{t=0} = 0, \quad i = 1, \dots, N. \quad (89)$$

Multiplying (89) by $2\rho_i$ and integrating with respect to x , we obtain

$$\begin{aligned} \frac{d}{dt} \left(\int_0^1 \rho_i^2 dx \right) = - \int_0^1 \left(\rho_i^2 \left(\frac{\partial v^{(1)}}{\partial x} \right) + 2\rho_i^{(2)} \rho_i \left(\frac{\partial v}{\partial x} \right) + 2\rho_i v \left(\frac{\partial \rho_i^{(2)}}{\partial x} \right) \right) dx, \\ i = 1, \dots, N. \end{aligned} \quad (90)$$

The terms on the right-hand side of (90) can be estimated as follows:

$$- \int_0^1 \rho_i^2 \left(\frac{\partial v^{(1)}}{\partial x} \right) dx \leq \left(\sum_{j=1}^N \left\| \frac{\partial u_j^{(1)}}{\partial x} \right\|_{L_\infty(0,1)} \right) \left(\int_0^1 \rho_i^2 dx \right), \quad i = 1, \dots, N,$$

$$\begin{aligned}
 -2 \int_0^1 \rho_i^{(2)} \rho_i \left(\frac{\partial v}{\partial x} \right) dx &\leq \left\| \rho_i^{(2)} \right\|_{L_\infty(Q_T)}^2 \left(\int_0^1 \rho_i^2 dx \right) + \\
 &+ N \sum_{j=1}^N \int_0^1 \left(\frac{\partial u_j}{\partial x} \right)^2 dx, \quad i = 1, \dots, N,
 \end{aligned}$$

$$\begin{aligned}
 -2 \int_0^1 \rho_i v \left(\frac{\partial \rho_i^{(2)}}{\partial x} \right) dx &\leq \int_0^1 \rho_i^2 dx + \left\| \frac{\partial \rho_i^{(2)}}{\partial x} \right\|_{L_\infty(0,T;L_2(0,1))}^2 \|v\|_{L_\infty(0,1)}^2 \leq \\
 &\leq \int_0^1 \rho_i dx + N \left\| \frac{\partial \rho_i^{(2)}}{\partial x} \right\|_{L_\infty(0,T;L_2(0,1))}^2 \left(\sum_{j=1}^N \int_0^1 \left(\frac{\partial u_j}{\partial x} \right)^2 dx \right), \quad i = 1, \dots, N.
 \end{aligned}$$

By the inclusions

$$\begin{aligned}
 \rho_i^{(2)} &\in L_\infty(Q_T), \quad \frac{\partial \rho_i^{(2)}}{\partial x} \in L_\infty(0, T; L_2(0, 1)), \quad i = 1, \dots, N, \\
 \frac{\partial u_i^{(1)}}{\partial x} &\in L_2(0, T; L_\infty(0, 1)), \quad i = 1, \dots, N,
 \end{aligned}$$

we obtain the estimates

$$\frac{d}{dt} \left(\int_0^1 \rho_i^2 dx \right) \leq C_{49}(t) \int_0^1 \rho_i^2 dx + C_{50} \sum_{j=1}^N \int_0^1 \left(\frac{\partial u_j}{\partial x} \right)^2 dx, \quad i = 1, \dots, N,$$

where $C_{49} = C_{49} \left(\left\{ \left\| \frac{\partial u_i^{(1)}}{\partial x} \right\|_{L_\infty(0,1)} \right\}_{i=1}^N, \left\{ \|\rho_i^{(2)}\|_{L_\infty(Q_T)} \right\}_{i=1}^N \right)$, $C_{49} \in L_2(0, T)$,

$C_{50} = C_{50} \left(\left\{ \left\| \frac{\partial \rho_i^{(2)}}{\partial x} \right\|_{L_\infty(0,T;L_2(0,1))} \right\}_{i=1}^N, N \right)$. We can apply the Gronwall inequality to get inequalities

$$\int_0^1 \rho_i^2 dx \leq C_{51} \sum_{j=1}^N \int_0^t \int_0^1 \left(\frac{\partial u_j}{\partial x} \right)^2 dx d\tau, \quad i = 1, \dots, N, \quad (91)$$

where $C_{51} = C_{51} (C_{50}, \|C_{49}\|_{L_1(0,T)})$.

Further, from equations (2) and boundary conditions (4) we obtain (see (28))

$$\frac{1}{2} \frac{d}{dt} \left(\sum_{i=1}^N \int_0^1 \rho_i^{(1)} u_i^2 dx \right) + \sum_{i,j=1}^N \nu_{ij} \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx =$$

$$\begin{aligned}
&= K \int_0^1 \rho \left(\frac{\partial v}{\partial x} \right) dx - \sum_{i=1}^N \int_0^1 \rho_i u_i \left(\frac{\partial u_i^{(2)}}{\partial t} \right) dx - \\
&\quad - \sum_{i=1}^N \int_0^1 \rho_i^{(1)} v u_i \left(\frac{\partial u_i^{(2)}}{\partial x} \right) dx - \sum_{i=1}^N \int_0^1 \rho_i v^{(2)} u_i \left(\frac{\partial u_i^{(2)}}{\partial x} \right) dx,
\end{aligned}$$

which implies

$$\begin{aligned}
&\frac{d}{dt} \left(\frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} u_i^2 dx + \sum_{i,j=1}^N \nu_{ij} \int_0^t \int_0^1 \left(\frac{\partial u_i}{\partial x} \right) \left(\frac{\partial u_j}{\partial x} \right) dx d\tau \right) = \\
&= K \int_0^1 \rho \left(\frac{\partial v}{\partial x} \right) dx - \sum_{i=1}^N \int_0^1 \rho_i u_i \left(\frac{\partial u_i^{(2)}}{\partial t} \right) dx - \\
&\quad - \sum_{i=1}^N \int_0^1 \rho_i^{(1)} v u_i \left(\frac{\partial u_i^{(2)}}{\partial x} \right) dx - \sum_{i=1}^N \int_0^1 \rho_i v^{(2)} u_i \left(\frac{\partial u_i^{(2)}}{\partial x} \right) dx. \quad (92)
\end{aligned}$$

We estimate the terms on the right-hand side of (92) as follows:

$$\begin{aligned}
K \int_0^1 \rho \left(\frac{\partial v}{\partial x} \right) dx &\leq \frac{C_1}{4} \sum_{i=1}^N \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx + C_{52} (C_1, K, N) \sum_{i=1}^N \int_0^1 \rho_i^2 dx, \\
- \sum_{i=1}^N \int_0^1 \rho_i u_i \left(\frac{\partial u_i^{(2)}}{\partial t} \right) dx &\leq \frac{C_1}{4} \sum_{i=1}^N \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx + \\
&\quad + C_{53} \left(C_1, \left\{ \left\| \frac{\partial u_i^{(2)}}{\partial t} \right\|_{L_2(0,1)} \right\}_{i=1}^N \right) \sum_{i=1}^N \int_0^1 \rho_i^2 dx, \\
- \sum_{i=1}^N \int_0^1 \rho_i^{(1)} v u_i \left(\frac{\partial u_i^{(2)}}{\partial x} \right) dx &\leq \\
&\leq C_{54} \left(\left\{ \left\| \frac{\partial u_i^{(2)}}{\partial x} \right\|_{L_\infty(0,1)} \right\}_{i=1}^N, N \right) \frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} u_i^2 dx, \\
- \sum_{i=1}^N \int_0^1 \rho_i v^{(2)} u_i \left(\frac{\partial u_i^{(2)}}{\partial x} \right) dx &\leq C_{55} \left(\left\{ \|u_i^{(2)}\|_{L_\infty(Q_T)} \right\}_{i=1}^N, N \right) \sum_{i=1}^N \int_0^1 \rho_i^2 dx +
\end{aligned}$$

$$+ C_{56} \left(\left\{ \left\| \frac{1}{\rho_i^{(1)}} \right\|_{L_\infty(Q_T)} \right\}_{i=1}^N, \left\{ \left\| \frac{\partial u_i^{(2)}}{\partial x} \right\|_{L_\infty(0,1)} \right\}_{i=1}^N \right) \frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} u_i^2 dx,$$

where $C_{53}, C_{56} \in L_1(0, T)$, $C_{54} \in L_2(0, T)$. Hence, from (92), using the relation

$$\sum_{i=1}^N \int_0^1 \rho_i^2 dx \leq C_{57}(C_1, C_{51}, N) \frac{C_1}{2} \sum_{i=1}^N \int_0^t \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx d\tau$$

proved above (see (91)), we deduce

$$\begin{aligned} & \frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} u_i^2 dx + \frac{C_1}{2} \sum_{i=1}^N \int_0^t \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx d\tau \leq \\ & \leq \int_0^t C_{58}(C_{52}, \dots, C_{57}) \left(\frac{1}{2} \sum_{i=1}^N \int_0^1 \rho_i^{(1)} u_i^2 dx + \frac{C_1}{2} \sum_{i=1}^N \int_0^\tau \int_0^1 \left(\frac{\partial u_i}{\partial x} \right)^2 dx ds \right) d\tau, \end{aligned}$$

where $C_{58} \in L_1(0, T)$, which yields the identities $\rho_i \equiv 0$, $u_i \equiv 0$, $i = 1, \dots, N$. Theorem 1 is proved.

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ALEXANDER EVGENYEVICH MAMONTOV
CHAIR OF FURTHER MATHEMATICS,
FEDERAL STATE INSTITUTION OF HIGHER EDUCATION «SIBERIAN STATE
UNIVERSITY OF TELECOMMUNICATIONS AND INFORMATION SCIENCE»,
86, ST. KIROVA,
630102 NOVOSIBIRSK, RUSSIA
Email address: aem@hydro.nsc.ru

DMITRY ALEXEYEVICH PROKUDIN
LAVRENTYEV INSTITUTE OF HYDRODYNAMICS OF THE SIBERIAN BRANCH OF THE
RUSSIAN ACADEMY OF SCIENCES,
15, PR. LAVRENT'ÉVA,
630090, NOVOSIBIRSK, RUSSIA
Email address: prokudin@hydro.nsc.ru

DMITRY ALEXANDROVICH ZAKORA
V.I. VERNADSKY CRIMEAN FEDERAL UNIVERSITY,
4, PR. VERNADSKOGO,
295007, SIMFEROPOL, RUSSIA
Email address: dmitry.zkr@gmail.com