HOMOGENIZATION OF CONVECTION-DIFFUSION EQUATION IN INFINITE CYLINDER

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Abstract. The paper deals with a periodic homogenization problem for a non-stationary convection-diffusion equation stated in a thin infinite cylindrical domain with homogeneous Neumann boundary condition on the lateral boundary. It is shown that homogenization result holds in moving coordinates, and that the solution admits an asymptotic expansion which consists of the interior expansion being regular in time, and an initial layer.

Introduction. The goal of the paper is to study the asymptotic behaviour of a solution to an initial boundary problem for a convection-diffusion equation defined in a thin infinite cylinder with homogeneous Neumann condition on its lateral boundary. We assume that the coefficients of the equation are periodic in the axial direction of the cylinder and that the period is of the same order as the cylinder diameter. The corresponding parabolic operator takes the form

\[ \partial_t u - \text{div} \left( a \left( \frac{x}{\varepsilon} \right) \nabla u \right) + \frac{1}{\varepsilon} \left( b \left( \frac{x}{\varepsilon} \right), \nabla u \right); \quad (1) \]

here \( \varepsilon \) is a small positive parameter, and we assume the standard uniform ellipticity conditions on \( a(y) \) and the boundedness of the entries of \( a(y) \) and \( b(y) \).

Notice that the scaling factor \( 1/\varepsilon \) is natural for the convection term. Indeed, if one wants to consider the long-term behaviour of a convection-diffusion process described by the equation

\[ \partial_s u - \text{div}(a(y)\nabla u) + (b(y), \nabla u) = 0 \]

in a fixed infinite cylinder, then making the diffusive change of variables

\[ x = \varepsilon y, \quad t = \varepsilon^2 s \]

leads to a convection-diffusion problem for operator (1) in a thin cylinder.

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Closely related problems for a convection-diffusion equation defined in the whole space have been considered in [6] and [1]. It was proved in particular that the homogenization takes place in moving coordinates \( (x, t) \mapsto (x - (\bar{b}/\varepsilon)t, t) \) with a constant vector \( \bar{b} \).

Homogenization problems for divergence form operators and systems in thin bounded domains have been investigated by many authors, we mention here the works [7], [10] and [11]. General homogenization theory results for parabolic equations can be found in [5] and [12].

In the paper we first prove uniform in \( \varepsilon \) a priori estimates for the solution. This requires integration in weighted spaces where the solution of the periodic adjoint cell problem is used as a weight. Then we construct the leading terms of the asymptotic expansion in moving coordinates, determine the effective speed, and obtain the estimates for the rate of convergence. Additional difficulty appearing in the problem under consideration is the dimension reduction issue. Indeed, the solutions of the original problem belong to variable Sobolev spaces, which makes the convergence analysis rather involved.

The paper is organized as follows. Section 1 contains the problem setup. In Section 2 we deal with a priori estimates and study auxiliary parabolic cell problems. In Section 3 we construct formal asymptotic expansion which includes the corresponding initial layers, the presence of the initial layer allows us to satisfy the initial condition in higher order approximations. Section 4 is devoted to the convergence analysis.

1. Problem statement. Let \( Q \) be a bounded domain in \( \mathbb{R}^{d-1} \) with the Lipschitz boundary \( \partial Q \). For any \( \varepsilon > 0 \), we denote by \( G_\varepsilon \) a thin infinite cylinder \( \mathbb{R} \times \varepsilon Q \) with the axis directed along \( x_1 \). The lateral boundary of the cylinder \( G_\varepsilon \) is denoted by \( \Sigma_\varepsilon = \mathbb{R} \times \partial(\varepsilon Q) \). We study the following non-stationary convection-diffusion equation:

\[
\begin{aligned}
\partial_t u^\varepsilon(t, x) + \mathcal{A}_\varepsilon u^\varepsilon(t, x) &= 0, \quad (t, x) \in (0, T) \times G_\varepsilon, \\
\mathcal{B}_\varepsilon u^\varepsilon(t, x) &= 0, \quad (t, x) \in (0, T) \times \Sigma_\varepsilon, \\
u^\varepsilon(0, x) &= \varphi(x_1), \quad x \in G_\varepsilon,
\end{aligned}
\]

where

\[
\begin{align*}
\mathcal{A}_\varepsilon u &= -\text{div}\left( a\left(\frac{x}{\varepsilon}\right) \nabla_x u \right) + \frac{1}{\varepsilon} \left( b\left(\frac{x}{\varepsilon}\right), \nabla_x u \right), \\
\mathcal{B}_\varepsilon u &= (a\left(\frac{x}{\varepsilon}\right) \nabla_x u, n),
\end{align*}
\]

and \( n \) stands for the exterior unit normal on \( \Sigma_\varepsilon \). We suppose that the following conditions are fulfilled:

(H1) \( Q \) is a Lipschitz bounded domain in \( \mathbb{R}^{d-1} \);

(H2) \( a_{ij}(y), b_j(y) \in L^\infty(G), \ i, j = 1, \ldots, d \), are 1-periodic functions with respect to \( y_1 \);

(H3) The matrix \( a(y) \) satisfies the uniform ellipticity condition, that is there exists a positive constant \( \Lambda \) such that, for almost all \( x \in \mathbb{R}^d \),

\[
\Lambda |\xi|^2 \leq \sum_{i,j=1}^d a_{ij}(y) \xi_i \xi_j, \quad \forall \xi \in \mathbb{R}^d.
\]

(H4) \( \varphi(x_1) \in C_0^\infty(\mathbb{R}) \).
**Definition 1.1.** A function \( u^\varepsilon(t, x) \) is said to be a weak solution of problem (2) in \((0, T] \times \mathbb{G}_\varepsilon\) if

\[
u^\varepsilon \in L^\infty[0, T; L^2_{\text{loc}}(\mathbb{G}_\varepsilon)] \cap L^2[0, T; H^1_{\text{loc}}(\mathbb{G}_\varepsilon)], \quad \varepsilon \in (0, T)
\]

and \( u^\varepsilon \) satisfies

\[
\int_0^T \int_{\mathbb{G}_\varepsilon} \left\{ -u^\varepsilon \partial_t \psi + (a^\varepsilon \nabla u^\varepsilon, \nabla \psi) + (b^\varepsilon, \nabla u^\varepsilon) \psi \right\} \, dx \, dt = \int_{\mathbb{G}_\varepsilon} \varphi(x_1) \psi(0, x) \, dx
\]

for any \( \psi \in L^2[0, T; H^1(\mathbb{G}_\varepsilon)] \) such that \( \partial_t \psi \in L^2[0, T; L^2(\mathbb{G}_\varepsilon)] \) and \( \psi(T, x) = 0 \).

We are interested in the asymptotic behaviour of \( u^\varepsilon(t, x) \), as \( \varepsilon \to 0 \). Notice that, for any \( \varepsilon > 0 \), the existence and the uniqueness of a generalized solution to problem (2) is given by classical theory (see, e.g., [8]).

2. **Some preliminary results.**

2.1. **A priori estimates.** In what follows we denote \( Y = [0, 1) \times Q \),

\[
\mathcal{A}v = -\text{div}(a(y) \nabla v) + (b(y), \nabla_y v), \quad \mathcal{B}v = (a(y) \nabla v, n);
\]

\[
\mathcal{A}^* p^* = -\text{div}(a \nabla p^*) - \text{div}(b p^*), \quad \mathcal{B}^* p^* = (a \nabla p^*, n) + (b, n) p^*,
\]

By the Krein-Rutman theorem and the Harnack inequality, the adjoint periodic problem

\[
\begin{aligned}
\mathcal{A}^* p^*(y) &= 0, & y &\in Y, \\
\mathcal{B}^* p^*(y) &= 0, & y &\in \partial Y, \\
p^*(y) &\text{ is periodic in } y_1,
\end{aligned}
\]

has a positive solution \( p^*(y) \in C(Y) \cap H^1(Y) \) such that

\[
0 < p^- \leq p^*(y) \leq p^+ < \infty.
\]

We fix the choice of \( p^* \) by the normalization condition

\[
\int_Y p^*(y) \, dy = 1.
\]

The goal of this section is to obtain a priori estimates for a non-stationary convection-diffusion equation stated in a thin infinite cylinder. Namely, we consider the following non-homogeneous problem:

\[
\begin{aligned}
&\partial_t u^\varepsilon(t, x) + \mathcal{A}_\varepsilon u^\varepsilon(t, x) = f(t, x), & (t, x) &\in (0, T) \times \mathbb{G}_\varepsilon, \\
&\mathcal{B}_\varepsilon u^\varepsilon(t, x) = \varepsilon g(t, x), & (t, x) &\in (0, T) \times \Sigma_\varepsilon, \\
u^\varepsilon(0, x) &= \varphi(x), & x &\in \mathbb{G}_\varepsilon.
\end{aligned}
\]

Multiplying the equation in (7) by \( p^*(x/\varepsilon) u^\varepsilon(x) \) and integrating the resulting relation by parts over \( \mathbb{G}_\varepsilon \), we obtain

\[
\begin{aligned}
&\frac{1}{2} \int_{\mathbb{G}_\varepsilon} \frac{\partial(u^\varepsilon)^2}{\partial t} p^*(x/\varepsilon) \, dx + \frac{1}{2} \int_{\mathbb{G}_\varepsilon} (u^\varepsilon(t, x))^2 A^*_\varepsilon p^*(x/\varepsilon) \, dx + \\
&+ \frac{1}{2} \int_{\Sigma_\varepsilon} (u^\varepsilon(t, x))^2 B^*_\varepsilon p^*(x/\varepsilon) \, d\sigma + \int_{\mathbb{G}_\varepsilon} (a^\varepsilon \nabla u^\varepsilon, \nabla u^\varepsilon) p^*(x/\varepsilon) \, dx = \\
&= \varepsilon \int_{\Sigma_\varepsilon} g(t, x) u^\varepsilon(t, x) p^*(x/\varepsilon) \, d\sigma + \int_{\mathbb{G}_\varepsilon} f(t, x) u^\varepsilon(t, x) p^*(x/\varepsilon) \, dx.
\end{aligned}
\]
Here we use the notations
\[ A^\varepsilon q(x) = -\text{div}(a(\frac{x}{\varepsilon})\nabla q(x)) - \frac{1}{\varepsilon} \text{div}(b(\frac{x}{\varepsilon}) q(x)), \]
\[ B^\varepsilon q(x) = (a(\frac{x}{\varepsilon})\nabla q(x), n) + \frac{1}{\varepsilon} (b(\frac{x}{\varepsilon}), n) q(x). \]
Taking into account the definition of \( p^*(y) \) we get
\[ \frac{1}{2} \frac{d}{dt} \int_{G_\varepsilon}(u^\varepsilon)^2 p^*(\frac{x}{\varepsilon}) \, dx + \int_{G_\varepsilon} (a^\varepsilon \nabla u^\varepsilon \cdot \nabla u^\varepsilon) p^*(\frac{x}{\varepsilon}) \, dx = \]
\[ = \varepsilon \int_{\Sigma_\varepsilon} g(t,x) u^\varepsilon(t,x) p^*(\frac{x}{\varepsilon}) \, d\sigma + \int_{G_\varepsilon} f(t,x) u^\varepsilon(t,x) p^*(\frac{x}{\varepsilon}) \, dx. \]

Using the positive definiteness of the matrix \( a(y) \), bounds (6), and the Cauchy-Bunyakovsky inequality, one can obtain
\[ \frac{1}{2} \frac{d}{dt} \int_{G_\varepsilon}(u^\varepsilon)^2 p^*(\frac{x}{\varepsilon}) \, dx + \Lambda p^{-} \int_{G_\varepsilon} |\nabla u^\varepsilon|^2 \, dx \leq \]
\[ + \frac{1}{2\gamma} \left\{ \int_{G_\varepsilon} (f(t,x))^2 \, dx + \varepsilon \int_{\Sigma_\varepsilon} (g(t,x))^2 \, d\sigma \right\} \]
\[ + \frac{\gamma}{2} p^+ \varepsilon \int_{\Sigma_\varepsilon} (u^\varepsilon)^2 \, d\sigma + \frac{\gamma}{2} p^+ \int_{G_\varepsilon} (u^\varepsilon)^2 \, dx \]
for any \( \gamma > 0 \). By the trace theorem
\[ \int_{\Sigma_\varepsilon} (u^\varepsilon)^2 \, d\sigma \leq \frac{C_1}{\varepsilon} \int_{G_\varepsilon} (u^\varepsilon)^2 \, dx + C_2 \varepsilon \int_{G_\varepsilon} |\nabla u^\varepsilon|^2 \, dx \]
with constants \( C_1, C_2 \) independent of \( \varepsilon \). Consequently, for a sufficiently small \( \gamma \),
\[ \frac{d}{dt} \left[ \int_{G_\varepsilon}(u^\varepsilon)^2 p^*(\frac{x}{\varepsilon}) \, dx + \int_0^t \int_{G_\varepsilon} |\nabla u^\varepsilon(s,x)|^2 \, dxds \right] \leq \]
\[ + C \left\{ \|f\|^2_{L^2(G_\varepsilon)} + \varepsilon \|g\|^2_{L^2(\Sigma_\varepsilon)} \right\} + \left[ \int_{G_\varepsilon}(u^\varepsilon)^2 p^*(\frac{x}{\varepsilon}) \, dx + \int_0^t \int_{G_\varepsilon} |\nabla u^\varepsilon(s,x)|^2 \, dxds \right]. \]

Integrating with respect to \( t \) and applying the Grönwall lemma and the positiveness of the function \( p^* \), one can see that
\[ \int_{G_\varepsilon}(u^\varepsilon)^2 \, dx + \int_0^t \int_{G_\varepsilon} |\nabla u^\varepsilon(s,x)|^2 \, dxds \leq \]
\[ \leq C e^{t} \left\{ \|f\|^2_{L^2[0,T;L^2(G_\varepsilon)]} + \varepsilon \|g\|^2_{L^2[0,T;L^2(\Sigma_\varepsilon)]} + \|\varphi\|^2_{L^2(G_\varepsilon)} \right\}, \quad t \in (0,T] \]
where the constant \( C \) does not depend on \( \varepsilon \), and depends only on \( \Lambda, d \) and \( Q \).

For the justification procedure we also need a priori estimates in the case of right-hand side being the divergence of a bounded vector-function. Namely, consider the
Grönwall’s lemma, for asymptotic behaviour of solutions to parabolic equations, as \( t \to \infty \).

2.2. Auxiliary results. In the sequel we will need the information about the asymptotic behaviour of solutions to parabolic equations, as \( t \to \infty \). Consider the following problem:

\[
\begin{aligned}
\begin{cases}
\partial_t u^\varepsilon(t, x) + A_\varepsilon u^\varepsilon(t, x) = \text{div}_x F(t, x), \\
B_\varepsilon u^\varepsilon(t, x) = -(F, n),
\end{cases}
\quad (t, x) \in (0, T) \times \mathbb{G}_\varepsilon,
\end{aligned}
\]

where \( u^\varepsilon(0, x) = 0, \quad x \in \mathbb{G}_\varepsilon, \) with \( F(t, x) \) such that

\[ |F(t, x)| \leq f_1(t, x) e^{-\gamma|x|}, \quad f_1 \in L^\infty((0, T) \times \mathbb{G}_\varepsilon). \]

Multiplying equation in (9) by \( p^*(\frac{x}{\varepsilon}) u^\varepsilon(x) \) and integrating by parts over \( \mathbb{G}_\varepsilon \), we obtain

\[
\frac{1}{2} \frac{d}{dt} \int_{\mathbb{G}_\varepsilon} (u^\varepsilon)^2 p^*(\frac{x}{\varepsilon}) \, dx + \int_{\mathbb{G}_\varepsilon} (a^\varepsilon \nabla u^\varepsilon, \nabla u^\varepsilon) p^*(\frac{x}{\varepsilon}) \, dx =
\]

\[
= - \int_{\mathbb{G}_\varepsilon} (F(t, x), \nabla u^\varepsilon(t, x)) p^*(\frac{x}{\varepsilon}) \, dx
\]

\[
- \int_{\mathbb{G}_\varepsilon} (F(t, x), \nabla p^*(\frac{x}{\varepsilon})) u^\varepsilon(t, x) \, dx \equiv I_1 + I_2.
\]

Exploiting the Couchy-Bunyakovsky inequality and taking into account (6) one gets

\[
|I_1| \leq \frac{b^+}{2\delta} \|F\|_{L^2(\mathbb{G}_\varepsilon)} + \frac{p^+}{2} \|\nabla u^\varepsilon\|_{L^2(\mathbb{G}_\varepsilon)}
\]

\[
\leq \frac{p^+}{\delta} \|f_1\|_{L^\infty((0, T) \times \mathbb{G}_\varepsilon)} \varepsilon^{d-1} + p^+ \|\nabla u^\varepsilon\|_{L^2(\mathbb{G}_\varepsilon)}, \quad \delta = \frac{p^- A}{p^+}.
\]

The integral \( I_2^* \) is estimated as follows

\[
|I_2^*| \leq \frac{1}{2} \int_{\mathbb{G}_\varepsilon} |(F, \nabla p^*(\frac{x}{\varepsilon}))|^2 \, dx + \frac{1}{2} \|u^\varepsilon\|_{L^2(\mathbb{G}_\varepsilon)}
\]

\[
\leq \sum_{n=\infty}^{+\infty} \|F\|_{L^\infty((\varepsilon y_n))} \int_{\varepsilon Y_n} |\nabla p^*(\frac{x}{\varepsilon})|^2 \, dx + \frac{1}{2} \|u^\varepsilon\|_{L^2(\mathbb{G}_\varepsilon)}
\]

\[
\leq \sum_{n=\infty}^{+\infty} \|F\|_{L^\infty((\varepsilon y_n))} \varepsilon^{d-2} \int_{Y_n} |\nabla p^*(y)|^2 \, dy + \frac{1}{2} \|u^\varepsilon\|_{L^2(\mathbb{G}_\varepsilon)}
\]

\[
\leq C \varepsilon^{d-1} \frac{1}{\varepsilon} \|f_1\|_{L^\infty((0, T) \times \mathbb{G}_\varepsilon)} + \frac{1}{2} \|u^\varepsilon\|_{L^2(\mathbb{G}_\varepsilon)},
\]

where \( Y_n = (n, n+1] \times Q \).

Finally, combining the obtained estimates for \( I_1^* \) and \( I_2^* \) with (10), and using the Grönwall’s lemma, for \( t \in (0, T) \) one has

\[
\int_{\mathbb{G}_\varepsilon} (u^\varepsilon)^2 \, dx + \int_0^t \int_{\mathbb{G}_\varepsilon} |\nabla u^\varepsilon(s, x)|^2 \, dx \, ds \leq \frac{C e^t}{\varepsilon} \varepsilon^{d-1} \|f_1\|_{L^\infty((0, T) \times \mathbb{G}_\varepsilon)}. \quad (11)
\]
initial boundary value problem
\[
\begin{aligned}
\partial_{\tau} v(\tau, y) + A v(\tau, y) &= 0, \quad (\tau, y) \in (0, \infty) \times Y, \\
B v(\tau, y) &= 0, \quad (\tau, y) \in (0, \infty) \times \partial Y, \\
v(\tau, y) - y_1 - \text{periodic}, & \quad y \in Y, \\
v(0, y) = \psi(y), & \quad y \in Y,
\end{aligned}
\]  
where \( Y = [0, 1) \times Q \).

Lemma 2.1. Suppose conditions (H1)–(H3) are fulfilled and \( \psi(y) \in L^2(Y) \). Then there exists a unique weak solution \( v \) to problem (12), and it stabilizes to a constant \( v^\infty \) at the exponential rate, as \( \tau \to \infty \), that is
\[
|v(\tau, y) - v^\infty| \leq C_0 \|\psi\|_{L^2(Y)} e^{-\gamma \tau}, \quad y \in Y, \quad \tau > 0,
\]
with positive constants \( C_0 \) and \( \gamma \) depending only on \( \Lambda, d \) and \( Q \). Moreover, \( \nabla_y v \) stabilizes exponentially to \( 0 \), as \( \tau \to \infty \):
\[
\int_{\tau}^{\tau+1} \int_Y |\nabla_y v(s, y)|^2 dyds \leq C e^{-2\gamma \tau}.
\]

The constant \( v^\infty \) is defined by
\[
v^\infty = \int_Y \psi(y) p^*(y) dy,
\]
where \( p^*(y) \) solves problem (5).

Proof. Let us consider two functions
\[
m(\tau) = \min_{y \in Y} v(\tau, y), \quad M(\tau) = \max_{y \in Y} v(\tau, y).
\]
By the maximum principle, \( M(\tau) \) decreases and \( m(\tau) \) increases. In view of the linearity of the problem, without loss of generality we assume that \( m(\tau_0) = 0 \). Since \( v \geq 0 \), then we can use the Harnack inequality
\[
m(\tau_0 + 1) \geq \alpha M(\tau_0 + 1), \quad \alpha < 1
\]
to obtain the estimate
\[
\text{osc}_{\tau=\tau_0+1} v(\tau, y) \equiv M(\tau_0 + 1) - m(\tau_0 + 1) \leq (1 - \alpha) M(\tau_0) \equiv (1 - \alpha) \text{osc}_{\tau=\tau_0} v(\tau, y).
\]
Consequently,
\[
\text{osc}_{\tau=\tau_0+1} v(\tau, y) \leq (1 - \alpha) \text{osc}_{\tau=\tau_0} v(\tau, y), \quad \tau_0 \geq 0
\]
and, obviously, \( v \) converges to some constant \( v^\infty \), as \( \tau \to \infty \)
\[
|v(\tau, y) - v^\infty| \leq C_0 \|\psi\|_{L^2(Y)} e^{-\gamma \tau},
\]
where \( C \) and \( \gamma \) depend only on \( \Lambda, d \) and \( Q \).

Let us calculate the constant \( v^\infty \). To this end we multiply the equation in (12) by \( p^* \) and integrate by parts over the set \( (0, \tau) \times Y \). As a result we obtain the following equality:
\[
\int_Y v(\tau, y) p^*(y) dy = \int_Y \psi(y) p^*(y) dy.
\]
Since \( v \) converges uniformly to the constant \( v^\infty \), as \( \tau \to \infty \), then it follows from the last equality that

\[
v^\infty = \int_Y \psi(y) p^*(y) \, dy,
\]

if \( p^* \) is normalized by \( \int_Y p^* \, dy = 1 \).

Now we prove estimate (14). Note that the function \( w = v - v^\infty \) solves the same equation as \( v \), and satisfies the initial condition \( w(0, y) = \psi - v^\infty \). Multiplying the equation by \( w \), integrating by parts and applying the Cauchy-Bunyakowski inequality gives

\[
\int_Y |w(\tau + 1, y)|^2 \, dy + \Lambda \int_0^{\tau+1} |\nabla w|^2 \, dy \, ds \\
\leq \Lambda^{-1} \frac{1}{2\eta} \int_0^{\tau+1} |w(s, y)|^2 \, dy \, ds + \frac{\Lambda^{-1}}{2} \int_0^{\tau+1} |\nabla yw(s, y)|^2 \, dy \, ds + \int_0^{\tau+1} |w(s, y)|^2 \, dy,
\]

and, consequently, choosing \( \eta < 2\Lambda^2 \) and using (13), we obtain

\[
\int_0^{\tau+1} |\nabla w|^2 \, dy \, ds \leq C e^{-2\gamma_1 \tau}.
\]

The next lemma generalizes the result of Lemma 2.1 to the non-homogeneous case. Consider the boundary value problem

\[
\begin{align*}
\partial_\tau v(\tau, y) + A v(\tau, y) &= f(\tau, y) + \text{div}_y F(\tau, y), \quad (\tau, y) \in (0, \infty) \times Y, \\
B v(\tau, y) &= g(\tau, y) - (F(\tau, y), n), \quad (\tau, y) \in (0, \infty) \times \partial Y, \\
v(0, y) &= 0, \quad y \in Y,
\end{align*}
\]

where \( f \in L^2[0, \infty; L^2(Y)] \), \( F \in L^2[0, \infty; L^2(Y)^d] \) and \( g \in L^2[0, \infty; L^2(\partial Y)] \) decay exponentially, as \( \tau \to \infty \), that is

\[
\int_0^{\tau+1} \|f(s, \cdot)\|_{L^2(Y)}^2 \, ds \leq C e^{-\gamma_1 \tau}; \quad \int_0^{\tau+1} \|F(s, \cdot)\|_{L^2(Y)^d}^2 \, ds \leq C e^{-\gamma_1 \tau}; \\
\int_0^{\tau+1} \|g(s, \cdot)\|_{L^2(\partial Y)}^2 \, ds \leq C e^{-\gamma_1 \tau}, \quad \gamma_1 > 0.
\]

**Lemma 2.2.** Under the assumptions being made, a solution of problem (15) satisfies the estimates

\[
\int_0^{\tau+1} \|v(s, \cdot) - v^\infty\|_{L^2(Y)}^2 \, ds \leq C e^{-\tilde{\gamma} \tau}, \quad \tilde{\gamma} > 0,
\]

\[
\int_0^{\tau+1} \|\nabla v(s, \cdot)\|_{L^2(Y)}^2 \, ds \leq C e^{-\tilde{\gamma} \tau}, \quad \tilde{\gamma} > 0.
\]
Here $C$ depends on $\Lambda, d$ and $Q$. The constant $v^\infty$ is determined by

$$v^\infty = \int_0^\infty \int_Y f(\tau, y) p^*(y) \, dy \, d\tau - \int_0^\infty \int_Y (F(\tau, y), \nabla p^*(y)) \, dy \, d\tau$$

$$+ \int_0^\infty \int_{\partial Y} g(\tau, y) p^*(y) \, d\sigma \, d\tau,$$

$p^*$ being a solution of (5).

**Proof.** First of all we represent the functions on the right-hand side of (15) as the sums of functions with finite supports, that is

$$f(\tau, y) = \sum_{m=\infty}^{+\infty} f_m(\tau, y), \quad F(\tau, y) = \sum_{m=\infty}^{+\infty} F_m(\tau, y), \quad g(\tau, y) = \sum_{m=\infty}^{+\infty} g_m(\tau, y),$$

where $f_m(\tau, y) = f(\tau, y) \chi_{[m, m+1)}$, $F_m(\tau, y) = F(\tau, y) \chi_{[m, m+1)}$, $g_m(\tau, y) = g(\tau, y) \chi_{[m, m+1)}$, and $\chi_{[m, m+1)}(\tau)$ is the characteristic function of the interval $[m, m+1)$.

Due to the linearity of the problem, the solution $v$ of (15) can be represented in the form

$$v(\tau, y) = \sum_{m=\infty}^{+\infty} v_m(\tau, y),$$

where $v_m$ solves the problem

$$\begin{cases}
\partial_\tau v_m + \mathcal{A} v_m = f_m(\tau, y) + \text{div}_y F_m(\tau, y), & (\tau, y) \in (0, \infty) \times Y, \\
\mathcal{B} v_m = g_m(\tau, y) - (F_m(\tau, y), n), & (\tau, y) \in (0, \infty) \times \partial Y, \\
v_m(0, y) = 0, & y \in Y.
\end{cases} \tag{18}$$

Notice that, in view of the uniqueness of the solution, $v_m(\tau, y) = 0$ for $\tau \in [0, m)$. Then, multiplying the equation in (18) by $v_m$ and integrating over $(m-1, m+2) \times Y$, we obtain

$$\int_Y (v_m(m+2, y))^2 \, dy \leq C \left( \int_0^\infty \|f(s, \cdot)\|_{L^2(Y)}^2 \, ds + \int_m^{m+1} \|g(s, \cdot)\|_{L^2(Y)}^2 \, ds \right) + \int_m^{m+1} \|F(s, \cdot)\|_{L^2(Y)}^2 \, ds \leq C e^{-\gamma_1 m}.$$

By Lemma 2.1, $v_m$ satisfies estimate (13) in $(m+2, \infty) \times Y$, namely,

$$|v_m(\tau, y) - v^\infty_m| \leq C e^{-\gamma_1 m} e^{-\gamma (\tau - m - 2)} \leq C e^{-\tilde{\gamma} \tau}, \quad \tau > m + 2,$$

for some constant $v^\infty_m$, where $\tilde{\gamma} = \min\{\gamma, \gamma_1\}$. In view of the maximum principle,

$$v^\infty_m \leq C e^{-\gamma_1 m}.$$
Let us show that \( v = \sum v_m \) stabilizes to \( v^\infty = \sum v_m^\infty \), as \( \tau \to \infty \). To this end we estimate the \( L^2 \)-norm of the difference \( v - v^\infty \).

\[
\int_N^{N+1} \|v(s, \cdot) - v^\infty\|_{L^2(Y)}^2 \, ds = \int_N^{N+1} \|\sum_{m=0}^{+\infty} (v_m(s, \cdot) - v_m^\infty)\|_{L^2(Y)}^2 \, ds = \\
= \int_N^N \|\sum_{m \leq N-2} + \sum_{m \geq N-1} \|v_m(s, \cdot) - v_m^\infty\|_{L^2(Y)}^2 \, ds \leq \\
\leq C_1 N^2 e^{-2\gamma N} + C_2 e^{-2\gamma N} \leq C e^{-\tilde{\gamma} N}, \quad \tilde{\gamma} > 0.
\]

The exponential decay of \( \nabla v \) can be proved in much the same way as in the homogeneous case.

\[\square\]

3. Asymptotic expansion.

3.1. Formal inner expansion. Following the ideas in [6] and [1], we are looking for an approximate solution in the form

\[
u^r \sim u_0(t, x_1 - \varepsilon^{-1} \bar{b}_1 t) + \sum_{k=1}^\infty \varepsilon^k v_k(t, x_1 - \varepsilon^{-1} \bar{b}_1 t, y), \quad y = \frac{x}{\varepsilon}, \tag{19}\]

where \( v_k, k \geq 1, \) are unknown functions which are 1-periodic in \( y_1, \) the constant \( \bar{b}_1 \) is to be determined.

Substituting (19) into (2) and collecting power-like terms in front of \( \varepsilon^{-1} \) in the equation and of \( \varepsilon^0 \) in the boundary condition, we obtain the following periodic problem for the unknown function \( v_1: \)

\[
\begin{aligned}
&\mathcal{A}_y v_1(t, x_1 - \varepsilon^{-1} \bar{b}_1 t, y) \\
&= (\partial_y a_{11}(y) - b_1(y) + \bar{b}_1) \partial_x u_0(t, x_1 - \varepsilon^{-1} \bar{b}_1 t), \quad y \in Y, \\
&\mathcal{B}_y v_1(t, x_1 - \varepsilon^{-1} \bar{b}_1 t, y) = -a_{11}(y) n_1 \partial_x u_0(t, x_1 - \varepsilon^{-1} \bar{b}_1 t), \quad y \in \partial Y;
\end{aligned} \tag{20}\]

Setting

\[
\bar{b}_1 = \int_y (a_{11}(y) \partial_y p^r(y) + b_1(y) p^r(y)) \, dy, \tag{21}\]

we guarantee that a solution to problem (20) exists. The specific form of the right-hand side of (20) suggests the following representation of \( v_1: \)

\[
v_1(t, x_1 - \varepsilon^{-1} \bar{b}_1 t, y) = N_1(y) \partial_x u_0(t, x_1 - \varepsilon^{-1} \bar{b}_1 t) + u_1(t, x_1 - \varepsilon^{-1} \bar{b}_1 t),
\]

where a \( Y \)-periodic function \( N_1 \) solves the problem

\[
\begin{aligned}
&\mathcal{A}_y N_1(y) = \partial_y a_{11}(y) - b_1(y) + \bar{b}_1, \quad y \in Y, \\
&\mathcal{B}_y N_1(y) = -a_{11}(y) n_1, \quad y \in \partial Y; \tag{22}\end{aligned}
\]
Similarly, we get the problem for \( v_2 \):

\[
\begin{align*}
A_y v_2(y, t, x_1 - \varepsilon^{-1}b_1 t, y) &= -\partial_t u_0(t, x_1 - \frac{b_1}{\varepsilon} t) \\
+ \{ a_{11}(y) + \partial_{y_i}(a_{i1}(y)N_1(y)) + a_{1j}(y)\partial_{y_j}N_1(y) \\
-b_1(y)N_1(y) + \tilde{b}_1N_1(y) \} \partial_{x_1}^2 u_0(t, x_1 - \frac{b_1}{\varepsilon} t) \\
+ \{ \partial_{y_i}a_{i1}(y) - b_1(y) + \tilde{b}_1 \} \partial_{x_1} u_1(t, x_1 - \frac{b_1}{\varepsilon} t), &\quad y \in Y, \\
B_y v_2(y) &= -a_{11}(y)N_1(y) u_i \partial_{x_i}^2 u_0(t, x_1 - \frac{b_1}{\varepsilon} t), &\quad y \in \partial Y.
\end{align*}
\tag{23}
\]

The compatibility condition for (23) gives rise to the Cauchy problem for \( u_0 \):

\[
\begin{align*}
\partial_t u_0(t, x_1) &= a_{11}^{\text{hom}} \partial_{x_1}^2 u_0(t, x_1), &\quad (t, x_1) \in (0, T) \times \mathbb{R}, \\
u_0(0, x_1) &= \varphi(x_1), &\quad x_1 \in \mathbb{R},
\end{align*}
\tag{24}
\]

where the constant \( a_{11}^{\text{hom}} \) is defined by

\[
a_{11}^{\text{hom}} = \int_Y \left[ a_{11}(y) + a_{1j}(y)\partial_{y_i}N_1(y) - b_1(y)N_1(y) \right] p^*(y) \, dy
\]

\[
+ \int_Y \left[ \tilde{b}_1N_1(y)p^*(y) - a_{11}(y)N_1(y)\partial_{y_i}p^*(y) \right] \, dy.
\]

The positiveness of \( a_{11}^{\text{hom}} \) has been proved in [9].

**Lemma 3.1.** The constant \( a_{11}^{\text{hom}} \) is strictly positive.

The form of the right-hand side of the equation in (23) suggests the following representation for the solution \( v_2 \):

\[
v_2(t, x_1 - \varepsilon^{-1}b_1 t, y) = N_2(y) \partial_{x_1}^2 u_0(t, x_1 - \varepsilon^{-1}b_1 t) \\
+ N_1(y) \partial_{x_1} u_1(t, x_1 - \varepsilon^{-1}b_1 t) + u_2(t, x_1 - \varepsilon^{-1}b_1 t)
\]

with \( y \)-periodic function \( N_2 \) being a solution of the problem

\[
\begin{align*}
A N_2(y) &= a_{11}(y) + \partial_{y_i}(a_{i1}(y)N_1(y)) + a_{1j}(y)\partial_{y_j}N_1(y) \\
-b_1(y)N_1(y) + \tilde{b}_1N_1(y) - a_{11}^{\text{hom}}, &\quad y \in Y, \\
B N_2(y) &= -a_{11}(y) u_i N_1(y), &\quad y \in \partial Y;
\end{align*}
\tag{25}
\]
Similarly, we obtain a boundary value problem for \( v_3 \)

\[
\begin{aligned}
A_y v_3(t, x_1 - \frac{1}{\varepsilon} t, y) &= -N_1(y)\partial_t \partial_{x_1} u_0(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) \bigg|_{r=t} \\
-\partial_t u_1(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) \bigg|_{r=t} + \left[ a_{11}(y)N_1(y) + \partial_y (a_{11}(y)N_2(y)) + a_{11}(y) \partial_{y_j} N_2(y) - b_1(y) N_2(y) + \tilde{b}_1 N_2(y) \right] \partial_{x_1}^2 u_0(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) \\
&\quad + \left[ a_{11}(y) + \partial_y (a_{11}(y) N_1(y)) + a_{11}(y) \partial_{y_j} N_1(y) + b_1(y) N_1(y) + \tilde{b}_1 N_1(y) \right] \partial_{x_1}^2 u_1(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) \\
&\quad + \left[ \partial_y a_{11}(y) - b_1(y) + \tilde{b}_1 \right] \partial_{x_1} u_2(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t), \quad y \in Y,
\end{aligned}
\]

\( B_y v_3(y) = -a_{11}(y) N_2(y) n_i \partial_{x_1}^3 u_0(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) \\
- a_{11}(y) N_1(y) n_i \partial_{x_1}^2 u_1(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t), \quad y \in \partial Y.
\]

From the compatibility condition for (26) we derive the equation for \( u_1 \):

\[
\partial_t u_1(t, x_1) = a_{11} \partial_{x_1}^2 u_1(t, x_1) + h_3 \partial_{x_1}^3 u_0(t, x_1), \quad (t, x_1) \in (0, T) \times \mathbb{R},
\]

where

\[
h_3 = \int_Y \left( -a_{11} N_1 p^* - \frac{a_{11} N_2}{\varepsilon} p - a_{11} N_2 \partial_y p^* - b_1 N_2 p^* + \tilde{b}_1 N_2 p^* \right) dy.
\]

Naturally, \( v_3 \) can be represented as the sum

\[
v_3(t, x_1 - \frac{1}{\varepsilon} t, y) = N_3(y) \partial_{x_1}^3 u_0(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) + N_2(y) \partial_{x_1}^2 u_1(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) + N_1(y) \partial_{x_1} u_2(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t) + u_3(t, x_1 - \frac{\tilde{b}_1}{\varepsilon} t),
\]

with \( N_3 \) being a \( y_1 \)-periodic solution of the cell problem

\[
A N_3(y) = a_{11}(y) N_1(y) + \partial_{y} (a_{11}(y) N_2(y)) + a_{11}(y) \partial_{y} N_2(y) - b_1(y) N_2(y) + \tilde{b}_1 N_2(y) - a_{11} \partial_{y_1} N_1(y) - h_3, \quad y \in Y,
\]

\[
B N_3(y) = -a_{11}(y) n_i N_2(y), \quad y \in \partial Y.
\]

Arguing as above, one can derive the equation for \( u_2 \)

\[
\partial_t u_2(t, x_1) = a_{11} \partial_{x_1}^2 u_2(t, x_1) \\
+ h_4 \partial_{x_1}^3 u_0(t, x_1) + h_3 \partial_{x_1}^2 u_1(t, x_1),
\]

where the constant \( h_4 \) is defined by

\[
h_4 = \int_Y \left( -a_{11} N_2 p^* + a_{11} N_2 p^* - a_{11} N_3 \partial_y p^* + b_1 N_3 p^* + \tilde{b}_1 N_3 p^* - h_3 N_1 \right) dy.
\]
Notice that determining initial conditions for $u_1$ and $u_2$ requires constructing initial layer correctors, which is done in Section 3.2.

Finally, as an inner approximate solution we take first three terms of (19)

$$u_{∞}(t, x) = u_0(t, x_1 - \frac{b_1}{ε} t) + ε \nu_1(\frac{x}{ε}) \frac{∂\nu_1(0, t, x_1 - \frac{b_1}{ε} t)}{∂x_1} \phi_{0}(t, x_1 - \frac{b_1}{ε} t)$$

$$+ ε u_1(t, x_1 - \frac{b_1}{ε} t) + ε^2 \nu_2(\frac{x}{ε}) \frac{∂\nu_2(0, t, x_1 - \frac{b_1}{ε} t)}{∂x_1} \phi_{0}(t, x_1 - \frac{b_1}{ε} t)$$

$$+ ε^2 \nu_1(\frac{x}{ε}) \frac{∂\nu_1(0, t, x_1 - \frac{b_1}{ε} t)}{∂x_1} \phi_{0}(t, x_1 - \frac{b_1}{ε} t)$$

3.2. Initial layers. The leading term $u_0(t, x_1)$ satisfies the initial condition $u_0(0, x_1) = φ(x_1)$. We introduce the initial layer functions, which will allow us to satisfy the initial condition up to the second power of $ε$. Consider the function $φ_1(τ, y)$ which is a solution to the problem

$$\begin{cases} \frac{∂ε \phi_1 + A_0 \phi_1 = 0, \quad (τ, y) ∈ (0, ∞) \times Y,} {B_0 \phi_1 = 0, \quad (τ, y) ∈ (0, ∞) \times ∂Y,} \\
φ_1(0, y) = −\nu_1(y). \end{cases}$$

By Lemma 2.1, $φ_1$ stabilizes to a constant $\bar{φ}_1$, as $τ → ∞$, at the exponential rate. The constant $\bar{φ}_1$ can be calculated as follows

$$\bar{φ}_1 = −\int Y \nu_1(y) p^*(y) dy. \quad (31)$$

We use this constant to set the initial value for $u_1$: $u_1(0, x_1) = \bar{φ}_1 φ'(x_1)$. In this way

$$\left[u_0(t, x_1 - \frac{b_1}{ε} t) + ε \nu_1(\frac{x}{ε}) \frac{∂\nu_1(0, t, x_1 - \frac{b_1}{ε} t)}{∂x_1} \phi_{0}(t, x_1 - \frac{b_1}{ε} t) + ε u_1(t, x_1 - \frac{b_1}{ε} t)

+ ε(\phi_1(\frac{t}{ε^2} \frac{x}{ε} - \bar{φ}_1) - \nu_1(0, t, x_1 - \frac{b_1}{ε} t)) \right]|_{τ=0} = φ'(x_1).$$

Similarly, we introduce $φ_2(τ, y)$ such that:

$$\begin{cases} \frac{∂ε \phi_2 + A_0 \phi_2 = 0, \quad (τ, y) ∈ (0, ∞) \times Y,} {B_0 \phi_2 = 0, \quad (τ, y) ∈ (0, ∞) \times ∂Y,} \\
φ_2(0, y) = −\nu_2(y); \end{cases}$$

The constant to which $φ_2$ stabilizes, as $τ → ∞$, we denote by $\bar{φ}_2$

$$\bar{φ}_2 = −\int Y \nu_2(y) p^*(y) dy, \quad (33)$$

and set

$$u_2(0, x_1) = \bar{φ}_2 φ''(x_1) + \bar{φ}_1 φ''(x_1).$$

In this way the boundary value problems for $u_1$ and $u_2$ take the form

$$\begin{cases} \frac{∂u_1(t, x_1) = d_{11}^∞ \frac{∂^2u_1}{∂x_1^2} u_1(t, x_1) + h_3 \frac{∂^3u_1}{∂x_1^3} u_0(t, x_1), \quad (t, x_1) ∈ (0, T) \times \mathbb{R},} {u_1(0, x_1) = \bar{φ}_1 φ'(x_1), \quad x_1 ∈ \mathbb{R};} \\
\end{cases} \quad (34)$$
\[
\begin{aligned}
\begin{cases}
\partial_t u_2(t, x_1) &= a_{11}^{\text{hom}} \partial_{x_1}^2 u_2(t, x_1) \\
+h_4 \partial_{x_1}^2 u_0(t, x_1) + h_3 \partial_{x_1}^3 u_1(t, x_1), & (t, x_1) \in (0, T) \times \mathbb{R},
\end{cases}
\end{aligned}
\]
with the constants \( h_3, h_4 \) defined in (27), (29). Then
\[
\begin{align*}
\varepsilon^2 N_2 \left( \frac{x}{\varepsilon} \right) \partial_{x_1}^2 u_0(t, x_1 - \frac{b_1}{\varepsilon} t) + \varepsilon^2 N_1 \left( \frac{x}{\varepsilon} \right) \partial_{x_1} u_1(t, x_1 - \frac{b_1}{\varepsilon} t) + \\
+ \varepsilon^2 q(t) g(x_1) + \varepsilon^2 u_2(t, x_1 - \frac{b_1}{\varepsilon} t) + \varepsilon^2 \left( \phi_2 \left( \frac{t}{\varepsilon^2}, \frac{x}{\varepsilon} \right) - \phi_2 \right) \varphi''(x_1) + \\
+ \varepsilon^2 \left( \phi_1 \left( \frac{t}{\varepsilon^2}, \frac{x}{\varepsilon} \right) - \phi_1 \right) \varphi''(x_1) \biggr|_{t=0} = 0.
\end{align*}
\]
Denote
\[
u^\varepsilon(t, x) = \varepsilon \left( \phi_1 \left( \frac{t}{\varepsilon^2}, \frac{x}{\varepsilon} \right) - \phi_1 \right) \varphi'(x_1) + \varepsilon^2 \left( \phi_2 \left( \frac{t}{\varepsilon^2}, \frac{x}{\varepsilon} \right) - \phi_2 \right) \varphi''(x_1) + \\
+ \varepsilon^2 \left( \phi_1 \left( \frac{t}{\varepsilon^2}, \frac{x}{\varepsilon} \right) - \phi_1 \right) \varphi''(x_1).
\]

We summarize this section by writing down the formal asymptotic expansion for a solution \( u^\varepsilon \) of problem (2) which has been constructed above. It reads
\[
U^\varepsilon(t, x) = u_0(t, x_1 - \frac{b_1}{\varepsilon} t) + \varepsilon N_1 \left( \frac{x}{\varepsilon} \right) \partial_{x_1} u_0(t, x_1 - \frac{b_1}{\varepsilon} t) + \\
+ \varepsilon u_1(t, x_1 - \frac{b_1}{\varepsilon} t) + \varepsilon^2 N_2 \left( \frac{x}{\varepsilon} \right) \partial_{x_1}^2 u_0(t, x_1 - \frac{b_1}{\varepsilon} t) + \\
+ \varepsilon^2 N_1 \left( \frac{x}{\varepsilon} \right) \partial_{x_1} u_1(t, x_1 - \frac{b_1}{\varepsilon} t) + \varepsilon^2 u_2(t, x_1 - \frac{b_1}{\varepsilon} t) + \nu^\varepsilon(t, x), \quad (t, x) \in (0, T) \times \mathbb{R}.
\]
Here \( u_0 \) is a solution of the homogenized problem (24); \( N_1, N_2 \) solve auxiliary cell problems (22), (25); \( u_1 \) and \( u_2 \) are solutions of nonhomogeneous Cauchy problems (34), (35); the initial layer \( u^\varepsilon_0 \) is given by (30)-(33) and (36). Notice that the approximate solution satisfies the initial condition: \( U^\varepsilon(0, x) = \varphi(x_1) \).

4. Justification procedure. In thin domain \( \Omega_\varepsilon \), it is natural to introduce the following notion of convergence (see, for example, [4, 13]).

**Definition 4.1.** We say that \( f_\varepsilon(t, x) \) converges strongly to zero in \( L^2[0, T; H^1(\Omega_\varepsilon)] \) if
\[
\varepsilon^{-\frac{d-1}{2}} \|f_\varepsilon\|_{L^2[0, T; H^1(\Omega_\varepsilon)]} \longrightarrow 0, \quad \varepsilon \rightarrow 0.
\]

The normalization factor \( \varepsilon^{-\frac{d-1}{2}} \) appears due to the fact that the norm of a fixed nontrivial \( C^\infty_0(\mathbb{R}) \) function \( \varphi(x_1) \) in the space \( L^2[0, T; H^1(\Omega_\varepsilon)] \) is of order \( \varepsilon^{\frac{d-1}{2}} \).

The following theorem is the main result of the paper.

**Theorem 4.2.** Let conditions (H1) – (H4) be fulfilled. Then the difference between the exact solution \( u^\varepsilon \) of problem (13) and the approximate solution \( \tilde{U}^\varepsilon \) given by (37), converges in \( L^2[0, T; H^1_0(\Omega_\varepsilon)] \) to zero, as \( \varepsilon \rightarrow 0 \). Moreover, the following estimate holds:
\[
\int_{\Omega_\varepsilon} (u^\varepsilon - \tilde{U}^\varepsilon)^2 dx + \int_0^t \int_{\Omega_\varepsilon} |\nabla (u^\varepsilon(s, x) - \tilde{U}^\varepsilon(s, x))|^2 dxds \leq C \varepsilon^2 \varepsilon^{d-1}.
\]
Proof. In order to estimate the norm (in the appropriate space) of the difference \( u^\varepsilon - U^\varepsilon \) between the exact and the approximate solutions, we calculate first \( A_\varepsilon(u^\varepsilon - U^\varepsilon) \) and \( B_\varepsilon(u^\varepsilon - U^\varepsilon) \), and then make use of a priori estimates (8), (11). Straightforward computations yield

\[
A_\varepsilon(u^\varepsilon(t, x) - U^\varepsilon(t, x)) = \varepsilon \left( R_1^\varepsilon(t, x) + R_2^\varepsilon(t, x) \right) + o(\varepsilon), \quad \varepsilon \to 0,
\]

where

\[
R_1^\varepsilon(t, x) = -\sum_{k=0}^{1} N_k\left(\frac{x}{\varepsilon}\right) \partial_k \partial_{x_1}^k u_{1-k}(t, x_1 - \frac{b_1}{\varepsilon} t)
\]

\[
+ \sum_{k=0}^{1} a_{11}\left(\frac{x}{\varepsilon}\right) \partial_{x_1}^{k+1} u_{2-k}(t, x_1 - \frac{b_1}{\varepsilon} t)
\]

\[
+ \sum_{k=0}^{1} a_{1j}\left(\frac{x}{\varepsilon}\right) \partial y_j N_k(y) \bigg|_{y=x/\varepsilon} \partial_{x_1}^{k+1} u_{2-k}(t, x_1 - \frac{b_1}{\varepsilon} t)
\]

\[
+ \sum_{k=0}^{1} b_1\left(\frac{x}{\varepsilon}\right) N_k\left(\frac{x}{\varepsilon}\right) \partial_{x_1}^{k+1} u_{2-k}(t, x_1 - \frac{b_1}{\varepsilon} t)
\]

\[
+ \sum_{k=1}^{2} \left( \phi_k(\tau, y) - \bar{\phi}_k \right) \varphi'''(x_1) + a_{11}(y) \left( \phi_1\left(\frac{t}{\varepsilon^2}, \frac{x}{\varepsilon}\right) - \bar{\phi}_1 \right) \varphi'''(x_1)
\]

\[
+ \sum_{k=1}^{2} a_{1j}(y) \nabla y_j \phi_k(\tau, y) \bigg|_{y=x/\varepsilon, \tau=t/\varepsilon^2} \varphi'''(x_1)
\]

\[
+ b_1(y) \sum_{k=1}^{2} \left( \phi_k\left(\frac{t}{\varepsilon^2}, \frac{x}{\varepsilon}\right) - \bar{\phi}_k \right) \varphi'''(x_1).
\]

\[
R_2^\varepsilon(t, x) = \sum_{k=0}^{2} \partial_{y_j} (a_{11}(y) N_k(y)) \bigg|_{y=x/\varepsilon} \partial_{x_1}^{k+1} u_{2-k}(t, x_1 - \frac{b_1}{\varepsilon} t)
\]

\[
+ \sum_{k=1}^{2} \partial_{y_j} (a_{11}(y)(\phi_k(\tau, y) - \bar{\phi}_k)) \bigg|_{y=x/\varepsilon, \tau=t/\varepsilon^2} \varphi'''(x_1).
\]

Similarly,

\[
B_\varepsilon(u^\varepsilon(t, x) - U^\varepsilon(t, x)) = \varepsilon^2 R_3^\varepsilon(t, x)
\]

with

\[
R_3^\varepsilon(t, x) = -\sum_{k=0}^{1} a_{11}\left(\frac{x}{\varepsilon}\right) n_i N_k\left(\frac{x}{\varepsilon}\right) \partial_{x_1}^{k+1} u_{2-k}(t, x_1 - \frac{b_1}{\varepsilon} t)
\]

\[
a_{1j}(y)n_i \sum_{k=1}^{2} \left( \phi_k\left(\frac{t}{\varepsilon^2}, \frac{x}{\varepsilon}\right) - \bar{\phi}_k \right) \varphi'''(x_1).
\]

By a priori estimates (8) and (11),

\[
\int_{\mathbb{G}_\varepsilon} (u^\varepsilon - U^\varepsilon)^2 \, dx + \int_0^t \int_{\mathbb{G}_\varepsilon} |\nabla (u^\varepsilon(s, x) - U^\varepsilon(s, x))|^2 \, dx \, ds
\]

\[
\leq C \varepsilon^T \left\{ \varepsilon \left\| R_1^\varepsilon \right\|_{L^2[0, T; L^2(\mathbb{G}_\varepsilon)]}^2 + \varepsilon^2 \left\| R_3^\varepsilon \right\|_{L^2[0, T; L^2(\mathbb{G}_\varepsilon)]}^2 + \frac{1}{\varepsilon} \left\| R_2^\varepsilon \right\|_{L^\infty((0, T) \times \mathbb{G}_\varepsilon)}^2 \right\}.
\]
In order to estimate $R_1^1$, $R_2^2$ and $R_3^3$, we analyze properties of the solutions $u_0$, $u_1$ and $u_2$ of problems (24), (34) and (35). For $u_0$ the well-known integral Poisson formula takes place:

$$u_0(t, x_1) = \frac{\theta(t)}{\sqrt{4\pi a_{11}^\text{hom} t}} \int_\mathbb{R} \varphi(\xi) e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} t}} d\xi.$$

Here $\theta$ is the unit step function, that is $\theta(t) = 1$ for $t \geq 0$, and $\theta(t) = 0$ when $t < 0$. Moreover, similar formula is valid for any derivative of $u_0$ with respect to $x_1$:

$$\partial_{x_1}^{(k)} u_0(t, x_1) = \frac{\theta(t)}{\sqrt{4\pi a_{11}^\text{hom} t}} \int_\mathbb{R} \partial_\xi^{(k)} \varphi(\xi) e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} t}} d\xi.$$

Bearing in mind that $\varphi$ has finite support, one can see that $|\partial_{x_1}^{(k)} u_0(t, x_1)| \leq C e^{-\alpha|x_1|^2}$, $C, \alpha > 0$, where $\alpha$ depends on $T$. Similarly, the following integral representation of $\partial_{x_1}^{(k)} u_1$ is valid:

$$\partial_{x_1}^{(k)} u_1(t, x_1) = \frac{\theta(t)}{\sqrt{4\pi a_{11}^\text{hom} t}} \int_\mathbb{R} \partial_\xi^{(k+1)} \varphi(\xi) e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} t}} d\xi + \frac{h_3}{\sqrt{\pi a_{11}^\text{hom} (t - \tau)}} \int_\mathbb{R} \partial_{x_1}^{3+k} u_0(\tau, \xi) e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} (t - \tau)}} d\xi = I_1 + I_2.

Arguing as above we obtain

$$|I_1| \leq C e^{-\alpha|x_1|^2}, \quad \alpha > 0.$$

Let us estimate $I_2$.

$$|I_2| \leq \left\{ \int_0^t d\tau \int_{|x_1 - \xi| \leq 2|x_1|} d\xi + \int_0^t d\tau \int_{|x_1 - \xi| > 2|x_1|} d\xi \right\} \frac{h_3}{\sqrt{\pi a_{11}^\text{hom} (t - \tau)}} \int_\mathbb{R} \partial_{x_1}^{3+k} u_0(\tau, \xi) e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} (t - \tau)}} d\xi.$$

In view of (39), for $\xi$ satisfying $|x_1 - \xi| \leq 2|x_1|$,

$$|\partial_{x_1}^{3+k} u_0(\tau, \xi) e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} (t - \tau)}}| \leq C e^{-\alpha_1 |\xi|^2} e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} (t - \tau)}} \leq C e^{-\alpha_1 |x_1|^2}, \quad \alpha_1 > 0,$$

thus,

$$\int_0^t d\tau \int_{|x_1 - \xi| \leq 2|x_1|} \frac{h_3}{\sqrt{\pi a_{11}^\text{hom} (t - \tau)}} e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} (t - \tau)}} d\xi \leq C |x_1| e^{-\alpha_1 |x_1|^2} \int_0^t \frac{1}{\sqrt{t - \tau}} d\tau \leq C e^{-\alpha_1 |x_1|^2}.$$

Noticing that

$$\frac{1}{\sqrt{4\pi a_{11}^\text{hom} t}} \int_\mathbb{R} e^{-\frac{|x_1 - \xi|^2}{4a_{11}^\text{hom} t}} d\xi = 1,$$
one has
\[ \int_0^t d\tau \int_{|x_1-\xi|>|2|x_1|} \frac{h_{3j} \partial^{\gamma_k}_{x_1} u_0(\tau, \xi)}{\sqrt{4\pi a_{\text{hom}}(t-\tau)}} e^{-\frac{|x_1-\xi|^2}{4a_{\text{hom}}(t-\tau)}} d\xi \leq C e^{-\alpha_1 |x_1|^2}, \quad \alpha_1 > 0. \]

In this way we see that \( u_1 \) satisfies the estimate
\[ |\partial^{\gamma_k}_{x_1} u_1(t, x_1)| \leq C e^{-\alpha_1 |x_1|^2}, \quad \alpha_1 > 0, \quad t \geq 0, \quad x \in \mathbb{R}. \]  

Arguing as above, one can see that analogous estimate holds for \( u_2 \) solving problem (35).
\[ |\partial^{\gamma_k}_{x_1} u_2(t, x_1)| \leq C e^{-\alpha_1 |x_1|^2}, \quad \alpha_1 > 0, \quad t \geq 0, \quad x \in \mathbb{R}. \]  

Bearing in mind the boundedness of the coefficients \( a_{ij}, b_j \), properties of \( N_1 \) and \( N_2 \) as the solutions of (22), (25), and bounds (39)-(41), one can check the validity of (38). Note that the exponential decay of the initial layer functions is used while estimating the corresponding terms.

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