International Journal of Thermal Sciences 113 (2017) 51–64

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Convective flows in a two-layer system with an interfacial heat release under the action of an imposed temperature gradient

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form
2 July 2016
Accepted 17 November 2016

Keywords:
Instabilities
Interface
Two-layer system

ABSTRACT

The influence of an interfacial heat release on nonlinear convective regimes, developed under the action of an imposed temperature gradient in the 47v2 silicone oil - water system, has been studied. Rigid heat-insulated lateral walls, corresponding to the case of closed cavities, have been considered. Transitions between the flows with different spatial structures, have been investigated. It is shown that the presence of an interfacial heat release can change the sequence of bifurcations and lead to the appearance of specific oscillatory regimes.

1. Introduction

Interfacial convection in systems with interfaces has been a subject of an extensive investigation at the past few decades (for a review, see Refs. [1,2]). Traditional fields of application of the interfacial convection are chemical engineering [3] and materials processing [4]. Among the modern techniques requiring an investigation of convection in systems with interfaces one can mention liquid encapsulation crystal growth technique used in space laboratories missions [5], droplet - droplet coalescence processes, where the Marangoni convection in the inter-droplet film can considerably affect the coalescence time during extraction [6], and others.

It is known that the stability problem for the mechanical equilibrium in a system with an interface is not self-adjoint (see Refs. [1,7]), thus an oscillatory instability is possible. The mechanism of oscillations, which develops without interfacial deformations due to the hydrodynamic and thermal interaction between convective flows on both sides of the interface, was found by Gershuni and Zhukhovitsky [8] in the case of transformer oil - formic acid system. However, the threshold value of the Rayleigh number for the oscillatory instability was higher than that for the monotonic instability. According to Gilev et al. (see Ref. [9]), if the ratio of the dynamic viscosities of fluids is reduced, the neutral curve has its minimum for oscillatory disturbances (see also [1]). Renardy [7] found that the same result can be obtained in the silicone oil - Fluorinert system if instead the “true” Fluorinert, a *fictitious* fluid with an enhanced thermal diffusivity of Fluorinert, is considered. The nonlinear oscillatory convective structures near the instability threshold for some model systems have been studied in Ref. [10].

An oscillatory instability of the mechanical equilibrium can be caused by the joint action of buoyancy and thermocapillary effect in a two-layer system heated from below. This phenomenon was described in Ref. [11] (see also [1,12]). Oscillations just above the instability threshold have been observed in experiments [13].

Under experimental conditions, the temperature gradient is not perfectly vertical and the horizontal component of the temperature gradient appears. The appearance of this component changes the situation completely: at any small values of the Marangoni number ($M \neq 0$), the mechanical equilibrium becomes impossible, and a convective flow takes place in the system. Thus, it is reasonable to consider the influence of the horizontal component of the temperature gradient on convective regimes developed in the system (see Refs. [14,15]). The Marangoni convection under the action of an inclined temperature gradient in two-layer systems, where the instability of a thermocapillary flow manifests itself in the form of hydrothermal waves or convective patterns, has been investigated

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.11.015
1290-0729/

in Ref. [16]. The influence of the horizontal component of the temperature gradient on convective oscillations in a two-layer system filling a closed cavity with *rigid heat-insulated lateral walls*, has been considered in Ref. [17]. It was shown that the horizontal component of the temperature gradient could lead to the violation of the symmetry conditions and the appearance of asymmetric oscillatory flows.

The interaction between convection caused by the temperature gradient directed perpendicularly to the interface and the convective flow produced by the horizontal component of the temperature gradient in *a laterally infinite two-layer system* in the presence of buoyant and thermocapillary effects, has been studied in Ref. [18]. Let us note that theoretical predictions obtained for the infinite layers cannot be automatically applied for the flows in closed cavities. In the case of periodic boundary conditions one observes waves generated by a convective instability of a parallel flow [19], while for the observation of waves in a closed cavity a global instability is needed.

There are various physical phenomena that can be the origin of a heat release on the interface. For example, an interfacial heat release accompanies an interfacial chemical reaction (see, e.g. [20]) and an interfacial heat consumption accompanies the evaporation [21].

The interfacial heating can be generated, e.g., by an infrared light source. The infrared absorption bands of water and silicone fluids are essentially different [22], therefore the light frequency can be chosen in a way that one of the fluids is transparent, while the characteristic length of the light absorption in another liquid is short.

Another possibility of the interfacial heating can be realized by the use of the ultra-violet radiation: the process of photolysis of hydrogen peroxide H_2O_2 due to the radiation with a wavelength lower than 400 *nm*, leads to the appearance of *OH_* radicals, accompanying by the reaction between silicone fluids and *OH_* radicals with an interfacial heat extraction [23].

The presence of a constant, spatially uniform heat release at the interface can lead to the appearance of an oscillatory instability [24]. The influence of an interfacial heat release on convective oscillations in the case of *rigid heat-insulated lateral walls* corresponding to a closed cavity, has been studied in Ref. [25].

In the present paper, the influence of an interfacial heat release on nonlinear convective regimes, developed under the action of an imposed temperature gradient in the 47v2 silicone oil - water system with *rigid heat-insulated lateral boundaries*, is studied. Cavities with different lengths, have been considered. It is shown that the presence of an interfacial heat release can change the sequence of bifurcations and lead to the appearance of steady and oscillatory flows in the system.

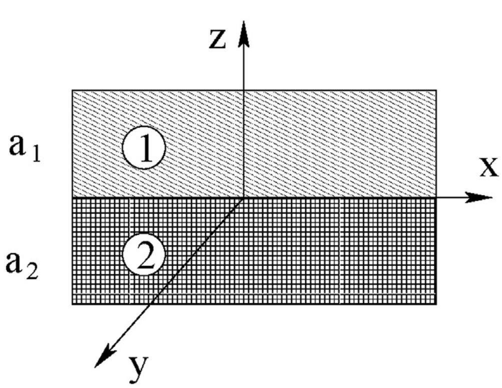

Fig. 1. Geometrical configuration of the two-layer system and coordinate axes.

The paper is organized as follows. In Section 2, the mathematical formulation of the problem in the two-layer system is presented. The nonlinear approach is described in Section 3. Nonlinear simulations of the finite-amplitude convective regimes are considered in Section 4. Section 5 contains some concluding remarks.

2. Formulation of the problem

We consider a system of two horizontal layers of immiscible viscous fluids with different physical properties (see Fig. 1). The variables referring to the top layer are marked by subscript 1, and the variables referring to the bottom layer are marked by subscript

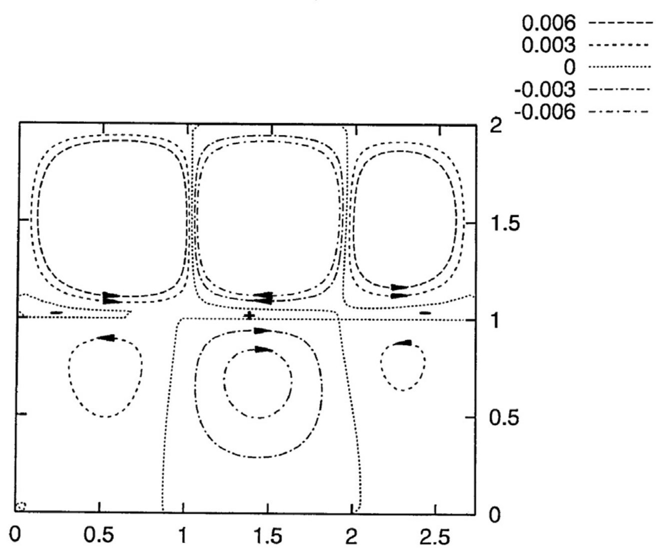

Fig. 2. Streamlines for the steady flow at $G = 107.7; K = 0.025; G_Q = 0; L = 2.74; \varepsilon = 0.01; a = 1$.

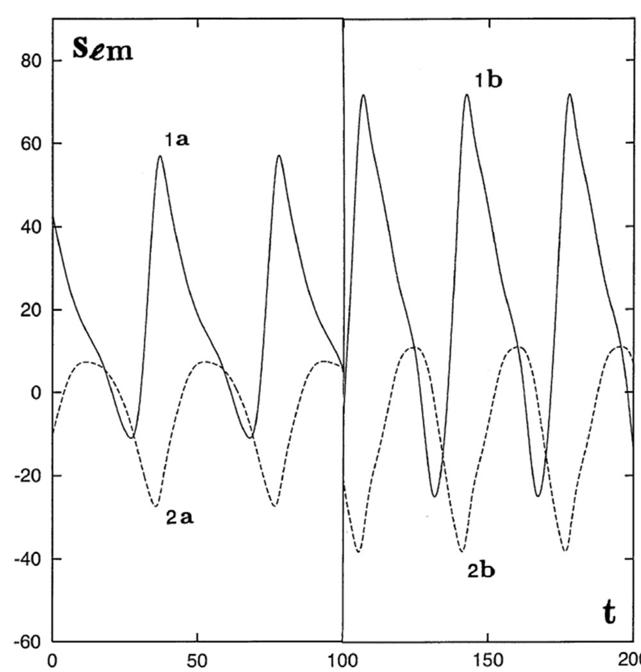

Fig. 3. Dependencies of $S_{l,m}$ on time ($m = 1,2$) for the asymmetric oscillatory flow at $G = 140.4$ (lines 1a, 2a); 162.1 (lines 1b, 2b); $K = 0.025$; $G_Q = 0$; $L = 2.74$; $\varepsilon = 0.01$; $a = 1$.