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FREE CONVECTION IN CLOSED CAVITIES: A REVIEW OF WORK CARRIED OUT AT PERM, USSR

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Аннотация—В 1946 г., в Перми были начаты экспериментальные и теоретические исследования тепловой конвекции. Работы проводились по следующим главным проблемам: тепловая конвекция в замкнутых полостях без образования пограничного слоя; конвективная устойчивость; устойчивость стационарных конвективных течений; замкнутый конвективный пограничный слой и его устойчивость; концентрационная конвекция; гидродинамические явления, сопровождающие прохождение электрического тока через жидкости; смежные конвективные проблемы; аппаратура и методика, используемые для экспериментальных исследований по конвекции; теория.

1. HEAT CONVECTION IN CLOSED CAVITIES WITHOUT BOUNDARY-LAYER FORMATION

WITH convection in closed cavities a boundary layer is not formed when the motion is sufficiently slow (weak convection). In some special cases a convective boundary layer does not appear even with fast motion up to turbulization if it is prevented by the cavity geometry. Steady convection in a long vertical cylinder and a slot are examples of such cases which have been investigated.

Convection in a long vertical cylinder heated from the bottom has been investigated in more detail. In [1] the main characteristics of the phenomenon are shown, namely: the existence of a sharp crisis of stability in a liquid with the onset of laminar motion; the retention of the vertical temperature gradient with such a motion; diametric antisymmetry of a flow and approximate parallelism of tube axis and jets under nonturbulent conditions. These characteristics allowed the proper formulation of a mathematical problem for a phenomenological determination. Its precise solution was also obtained for the case of steady laminar convection in a vertical slot embedded in a large block with an arbitrary direction of temperature gradient in the block remote from the slot. This solution [2] was generalized for the case of the superposition [3] of free and forced convection. Unsteady convection in a vertical cylinder was studied in [1, 4, 5]. Effects of finite size and phenomena associated with heat losses through lateral walls of a slot [4] were studied too.

The results of these studies are generalized in [6]. This reference deals with the following experimental and theoretical information: detailed description of experimental apparatus, models and methods of investigation (temperature recording method, optical method, etc.); heat transfer in a vertical duct in sub- and supercritical (turbulent) regimes; end effects; experimental study of heat convection in inclined slots of round section; convection in the air during water evaporation from a round slot; theoretical study of the thermal rôle of duct (tube) walls and heat losses through imperfect thermal insulation; theoretical study of unsteady heat convection applied to the cooling processes of liquid metal in moulds; theoretical and qualitative experimental (by optical grid method) investigation of convection in a slot and a horizontal cylinder; theoretical and experimental investigation of convection in a spherical cavity; some allied questions. Investigations of heat convection in cylindrical tubes were followed by heat-flux calculation with convection [7], velocity- profile measurements in a viscous liquid [8], and the investigation of convection in a short vertical cylinder [111] as well as by the observation of convection in conical tubes [9]. Works [10, 11] are devoted to an accurate experimental investigation of heat convection in water-filled glass cylindrical tubes heated from the bottom and inclined to the vertical line at an angle up to 85°. Great similarity has been noted between convective processes in tubes inclined up to 45° and in vertical slots (threshold effects, the critical Rayleigh number constancy, etc.). By contrast, heat losses through imperfect insulation essentially change the character of the convective flow patterns, as may be surmised from the experiments on the air convection in inclined tubes [12, 112]. In experiments with inclined mercury-filled glass tubes it was found that the range of heat fluxes transported upwards by a laminar convective flow narrows (up to fourfold for mercury as compared with more than thousandfold for water [13]). Suspensions of light-scattering particles in the convective flow evince zig-zag motion [14]. It is pointed out that some phenomena found experimentally cannot be explained by the available theories [15].

2. LIQUID STABILITY AND THE STABILITY OF STEADY FLOW HEAT CONVECTION

Mechanical equilibrium of a uniformly heated liquid is possible only when the temperature gradient in the liquid is constant, small and vertically directed. In the case of heating from below, convection appears spontaneously only when the critical ("threshold") value of the Rayleigh number is attained. With the antisymmetric steady motion which is characteristic in a vertical slot heated from below when the amount of heating exceeds the threshold one, the Rayleigh number remains constant and equal to the critical one over a rather wide range of applied heat fluxes [6], which considerably eases the study of convection stability. The critical Rayleigh number theoretically calculated for this case depends in a complicated manner on the relation between heat conductivity of walls and liquid [6]. This dependence was confirmed experimentally [16].

With sufficiently high heat fluxes, antisymmetric laminar flow is divided into cells along the tube length [1, 6]. Theory and experiment showed that the Rayleigh numbers corresponding to cellular convection in the tube increase with decreasing axial dimensions of the cells and depend on the relation between heat conductivity in tube walls and liquid [17]. The stability of steady convective liquid flow in a long vertical slot was experimentally investigated in [18]. In a horizontal cylinder heated from below cellular motion appearing due to three-dimensional disturbances was found in [19] in addition to plane motion. The Rayleigh number implies the conventional product of the Prandtl and Grashof numbers, the temperature difference of the latter one is replaced by the product of the mean axial temperature gradient by the tube radius (or slot width). The vertical dimension of the apparatus is also replaced by the tube radius (or slot width). The axial temperature gradient is taken for the middle part of the tube or slot remote from their end portions.

3. THE CLOSED CONVECTIVE BOUNDARY LAYER AND ITS STABILITY

In closed cavities at sufficiently high temperature differences convective boundary layer formation precedes flow turbulization and can transport substantial amounts of heat. In [20] the properties of a closed convective layer and the structure of immobile central core formation were studied experimentally in a spherical cavity with lateral heating and at Rayleigh numbers exceeding 10^4. The velocity profile in a boundary layer and the local heat transfer on the cavity wall are described by laws characteristic of a laminar convective layer under the conditions of the external problem. This is indicative of weak interaction of warm and cold convective flows near the cavity walls. Slow circular flows are found in the core which are opposite to the rotation in the boundary layer. Similar laws were noticed in studying convection in a short slot [21].

The amount of heat transferred over the cavity and the stability of closed boundary layer essentially depend on the heat flux direction with respect to the vector of gravity acceleration. The study of this question is presented in [22, 23]. High temperature gradients appearing in a laminar convective layer may cause mirages in a liquid [24] and substantial distortions of images in optical tubes [25].

In [26] the influence is studied of the effect of non-isothermal vertical heat transfer with a surface immersed in water, on the boundary layer and heat transfer. The properties of the boundary layer in a free-shaped cavity are theoretically discussed in [27].

4. CONCENTRATION CONVECTION

Concentration convection in vertical and slightly inclined tubes filled with aqueous sugar or blue vitriol solutions were studied in [28]. The similarity of the phenomena in concentration and thermal convections in tubes has been established. As for thermal convection [6], the solution of equations for steady concentration convection corresponding to experimental data is presented in the above paper.

Since the molecular weight of water vapours is less than that of air, concentration convection appears over the surface of water in its evaporation in a vertical tube [6, 29, 113]. Concentration and thermal diffusion effects may considerably influence the process of thermal convection in solutions [30].

5. HYDRODYNAMIC PROCESSES ASSOCIATED WITH ELECTRIC CURRENT FLOW THROUGH LIQUIDS

The investigations covered not only heat-transfer processes (energy conservation law) in thermal convection, and mass-transfer processes (matter conservation law) in concentration convection, but also the hydrodynamics of electric charges (electric-charge conservation law). Here, in contrast with magnetohydrodynamics, processes are discussed with negligible magnetic fields but at the same time with a substantial influence of displacement currents. It follows from rather general considerations that liquid (insulating liquid or strongly diluted electrolyte) placed between fixed charged electrodes cannot remain at rest when the intensity of electric field is sufficient [31–33]. The motion of a liquid non-uniform in conductivity and placed in electric field is studied in [34]. Electric current flow through insulating liquids is accompanied by a number of complicated hydrodynamic processes [35]. These processes may cause deviations from Ohm's law to be found in the measurement of the specific electric conductivity of some liquids [36].

Aerodynamic processes accompanying a corona discharge in air were studied in [37, 38]. Some peculiarities of this phenomenon allow a practical application to be suggested, which is similar to electronic amplifier valve operation [39].

6. OTHER CONVECTION PROBLEMS

Unsteady convection under the conditions of the external problem—near a horizontal cylinder—was experimentally studied in [40–42]. References [43, 44] are devoted to a theoretical investigation into steady convective heat transfer of a rotating solid.

7. APPARATUS AND METHODS USED FOR EXPERIMENTAL INVESTIGATION OF CONVECTION

The majority of the above works deal with this problem to some extent. In [45] simple interpolation formulae are given for evaluating a set of convective material properties of water and air over a wide temperature range. The problems dealing with the development of the optical grid method are discussed in [46, 47]. Convection study in a sphere [20] led to the development of a simple method for the treatment of experimental results [48]. A semi-empirical method is proposed of introducing corrections into the readings of thermocouples which control the temperature of a massive surface in convective heat transfer [49–51].

8. THEORY

As far as theory is concerned, all the works may be classified according to the main problems: 1. weak convection, the low-parameter method; 2. the theory of stability of liquid equilibrium when heated from below; 3. the stability of steady-state convective motion; 4. convection in a mixture; 5. the convective boundary layer; 6. some problems of magnetohydrodynamics.

1. *Weak convection, small parameter method*

Due to the complexity of the equations describing convective processes, the development of approximate methods to solve particular convective problems is necessary. A method [52] based on series expansion of the required functions in terms of a small parameter, i.e. the Grashof number, was proposed for thermal convection. This dimensionless parameter defined the intensity of thermal processes in a liquid medium. Thus, the solutions obtained by this method describe "weak" convection in a cavity without a threshold, i.e. with lateral heating. The method allows a number of problems to be solved: the problems of steady convection in horizontal tubes of different sections [53, 56–58, 62]; in a spherical cavity and in a bed bounded by two concentric spheres [54, 55, 59, 60]; in an inclined tube [61]. The method is extended to the solution of non-stationary problems [63–65]. The singularity of solutions and convergency of approximations were discussed in [66–68]. The method of series expansion in terms of Grashof number permits effective investigation into convective processes with the Grashof number less than critical.

Some precise solutions to thermal convection equations which describe steady convection in vertical and inclined channels of various sections were found, based on the assumption that the liquid velocities were parallel to the axis of the channel [69–71]. In some cases a precise solution is found allowing for temperature dependence of viscosity [72].

2. *Theory of stability of liquid equilibrium when heated from below*

This problem was undertaken by Rayleigh as far back as 1916. This problem has now been taken much further. The general stability theory was published in [73]. Using the variational method the general results were obtained on small-scale disturbances of equilibrium in arbitrary shaped cavities, a range of peculiarities of critical disturbances and critical temperature gradients were revealed, in the presence of which instability appears. Investigations were started of the stability of relatively finite disturbances [74], the data having been obtained on non-linear motions which appear under instability conditions of a liquid when small disturbances are developing.

Some particular problems of liquid stability were solved, involving cavities of various shapes, which allow equilibrium when the cavity is heated from below. Those cavities comprised a vertical elliptic cylinder [76], vertical cylindrical layer [78], a sphere [77] and a horizontal cylinder [75, 79]. When the stability of liquid equilibrium in cavities of various shapes was investigated, the Galerkin method [75–107] was used which allowed the smallest values of the minima of the Grashof numbers to be very accurately defined, their critical values to be found and the corresponding flow shapes to be estimated.

3. *Stability of steady convective motions*

The stability properties of steady convective motions were elucidated from the problem of convection between sloped parallel planes at various temperatures [80]. The application of the Galerkin method allowed the solution of the equations for steady-state flow disturbances and investigation of its stability in various particular cases. In particular, it was established that there existed two types of flow instability, i.e. relatively stagnant and relatively moving disturbances [82]. These two types of disturbances are responsible for the crisis of the steady-state flow under various conditions: in the case of the sloped layer—at various inclinations to the vertical line [81], in case of the vertical layer—at various Prandtl numbers [82]. The role of viscosity depending on temperature is elucidated in [83]. The problem of the stability of steady motion of a liquid in a finite-length slot has been solved for the case when a longitudinal temperature gradient appears.

4. *Heat convection in mixtures*

The equations have been obtained which describe convection in two-liquid mixtures taking account of cross kinetic effects [87] and some methodological questions on the definition of hydrodynamic parameters of mixtures and diffusion phenomena [85, 86] have been elucidated. Some particular problems on convection in a mixture have been solved [89] and the appearance ("threshold") of convection has been discussed on the assumption of monotonic disturbances in vertical cylinder [88] and in an arbitrary shaped cavity. In contrast to a pure liquid, a mixture may possess instability of relatively oscillating disturbances; the spectrum structure of convective instability of the mixture in the gravity field has been studied by using as an example a vertical layer of the mixture with vertical temperature and concentration gradients [90].

5. *Convective boundary layer*

When there are large temperature differences in the cavity, convective phenomena are characterized by the appearance of a convective boundary layer, whose properties are different from those of the viscous boundary layer of isothermal hydrodynamics. The problem of the convective boundary layer above a horizontal linear heat source [91] has been solved. It is reduced to the solution of ordinary differential equations, whose asymptotic solution is found. The problem is considered on a closed boundary layer which appears in the cavity at great temperature differences in it [92, 93]. The application of the integral method allowed the parameters of the boundary layer and the core covered by it to be defined and heat flow through the cavity to be calculated.

6. *The influence of a magnetic field on convective stability of a conducting liquid*

The results of the general convection theory [73] were applied to the case of equilibrium stability of the conducting media of relatively monotonic disturbances [95]. The problem of the equilibrium stability in a vertical cylinder in a magnetic field has been approximately solved [94]. The spectrum of convective stability in the conducting medium has been studied for the vertical [98] and the horizontal [108] plane layer, where the problem is accurately solved and reveals the main property of the spectrum: in strong fields and with definite correlation between the parameters of a liquid there appears an oscillating instability. The condition for the appearance of oscillating disturbances in general form has been found [109].

The influence of a magnetic field on the stability of steady convective motion has been observed by using as an example the motion of a conducting liquid between vertical parallel planes [98]. Critical Grashof numbers have been found depending on the magnetic-field intensity. Stagnant and moving disturbances [82] have been observed in the presence of the field as well; they are responsible for the instability of motion at various intensities of the magnetic field.

Some problems have been solved in the magnetohydrodynamic theory of flow: viscous flow of a conducting liquid round a sphere in a strong magnetic field [100], rotation of a sphere in a conducting liquid in a longitudinal field with the Stokes approximation [101] and under the conditions of boundary-layer formation [102].

The problem involving the stability of a flat horizontal liquid layer with a periodic change in the vertical temperature gradient (parametric excitation of the convective instability) is considered [110].

In addition some hydrodynamic problems are discussed: sound absorption in two-liquid mixture [103], in an electrolyte [104]; thermoelectric and thermomagnetic convection [105]; the correlation between various criteria of gas stability in the gravitational field [106]; turbulent regime of convection [107], etc.

This review covers the works of the physicists at Perm only. The results of the works of other Soviet physicists are not included into it, nor are those originating in other countries. This was done in order to keep down the length of this review to a reasonable limit.

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Abstract—Experimental and theoretical investigations of heat convection were started at Perm in 1946. The works were carried out on the following main problems: heat convection in closed cavities without boundary-layer formation; convective stability; the stability of steady convective flows; the closed convective boundary layer and its stability; hydrodynamic phenomena during the flow of electric current through fluids; allied convective problems; apparatus and methods; theory.

Résumé—Des recherches théoriques et expérimentales sur la convection de la chaleur ont commencé à Perm en 1946. Les travaux ont été conduits sur les problèmes principaux suivants: convection de la chaleur dans des cavités fermées sans formation de couche limite; stabilité convective; la stabilité des écoulements permanents de convection; la couche limite convective fermée et sa stabilité; phénomènes hydrodynamiques pendant le passage de courant électrique à travers des fluides; problèmes de convection voisins; appareillage et méthodes.

Zusammenfassung—1946 wurden in Perm experimentelle und theoretische Untersuchungen über den Wärmeübergang durch Konvektion begonnen. Diese Arbeiten wurden für folgende Probleme durchgeführt: Konvektion in geschlossenen Hohlräumen ohne Grenzschichtbildung; konvektive Stabilität; Stabilität von stationären Konvektionsströmungen; geschlossene konvektive Grenzschicht und ihre Stabilität; hydrodynamische Phänomene bei von elektrischem Strom durchsetzten Flüssigkeiten; verwandte konvektive Probleme; Apparatur und Messverfahren.