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PRINCIPLES OF THE DYNAMIC MECHANISM OF UNFORCED CONVECTION OF CONTINUA UNDER ORDINARY CONDITIONS

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It is found that, according to basic principles of mechanics and thermodynamics, there exist means for affecting continuum flow by heat which were not previously allowed for by the theory. These means are able to provide a circulation flow which does not attenuate with time.

It is well known that, under a rather small effect of viscous friction and a high-power thermal effect on a fluid medium, a stationary circulation flow of this medium is possible that is not forced by mechanical work over the circulation flow [1, 2]. We determine the ways of heat effect due to which such unforced convection is possible in principle (i.e., according to the basic laws of physics and thermodynamics) under general conditions of viscous friction forces, pressure, and a uniform gravity field (q = const). For simplicity and certainty we consider a stationary one-dimensional circular flow of a variable cross-section area (see Fig. 1) in the absence of mass transfer, heat conduction along the flow axis, and motion of medium, whose state is determined by two parameters. According to Newton's second and third laws, the law of mass conservation, and the first two principles of thermodynamics the following relations hold:

$$Gdu = -dF - g\rho fdh - d(pf) + pdf \equiv -dF - fdp - g\rho fdh\,, \tag{1}$$

$$dG = 0\,,\ \ di = Tds + vdp\,,\ \ ds = dQ/T = dN/(TG)\,, \tag{2}$$

where $G = \rho uf \neq 0$; i is the specific enthalpy as a function of $i(p, s)$ with its first partial derivatives being $i'_p = v \equiv 1/\rho$, $i'_s = T$, and for other derivatives the relations are valid

$$v'_s = T'_p = i''_{sp}\,,\ \ i''_{ps} = v'_s \equiv v\beta\,,\ \ i''_{pp} = v'_p \equiv -v\gamma\,,\ \ i'''_{pps} = v''_{ps} \equiv -v(\beta\gamma + \gamma'_s)\,; \tag{3}$$

$\beta \lesseqgtr 0$ is a quantity allowing for the direct effect of heat on the volume via thermal expansion, with the complex $\beta c_p/T$ being the temperature coefficient of volumetric isobaric expansion [2]; v''_{ps} is a quantity characterizing the indirect effect of heat on the volume by a change in compressibility; this effect is possible only with a change in static pressure (e.g., in the absence of thermal expansion, the specific volume changes under the effect of heat on $v''_{ps}dpds = -v\gamma'_s dpds$; see the right-hand expression in (3) at $\beta = 0$, an indirect effect of heat on the volume is possible for $\gamma'_s dp \neq 0$); the force of viscous friction, if it is directed opposite the flow, is traditionally taken to be positive. Having divided (1) by $f \neq 0$, we obtain

$$dp = -dF/f - \rho gdh - \rho udu \equiv -dF/f - \rho gdh - \rho du^2/2\,. \tag{4}$$

Having multiplied (4) by v, we have

$$vdF/f = -vdp - gdh - du^2/2\,. \tag{5}$$

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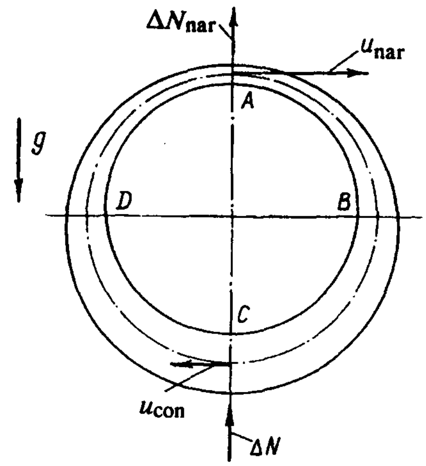

Fig. 1. Schematic of one-dimensional stationary unforced flow of continuum caused by the effect of heat in a contour of a variable cross-section area: *ABD*, diffusor; *CDA*, confusor; ΔN_{nar}, ΔN, powers of the effect of heat in narrow and wide portions, respectively; u_{nar}, u_{con}, flow velocities in front of *ABC* and *CDA*, respectively.

Equations (1), (4), and (5) describe motion in the most widespread concepts of mechanics (force, static pressure, mechanical energy) and do not allow for the effect of heat explicitly, thus making it impossible to study this effect of flow behavior analytically.

We now describe motion in terms of total pressure p_*, which changes for $u \neq 0$ only due to the influence of energy. Differentiating the well-known equality $i_* - i \equiv i(p_*, s) - i(p, s) = u^2/2$ (it is easily obtained by integrating (2), (5) at $dF/f = \rho g dh = 0 = ds$), we find

$$di_* - di = v_* dp_* - v dp + (i_* - i)_s' \, ds = u du \,, \tag{6}$$

where

$$(i_* - i)_s' = T_* - T \equiv \int_p^{p_*} T_p' dp_{id} = \int_p^{p_*} v_s' dp_{id} \equiv [v_s']_{id} (p_* - p) \,; \tag{7}$$

in (7) the quantity dp_{id} is the pressure increment during ideal retardation without energy effects, and the left-hand equality of (3) is taken into account; $[v_s']_{id}$ is some numerical value of v_s', the mean in a process of ideal retardation. From the right-hand equality of (6) we find

$$dp_* = \rho_* v (dp + \rho u du) - \rho_* (i_* - i)_s' \, ds \,, \tag{8}$$

where, according to (4):

$$(dp + \rho u du) = - dF/f - \rho g dh \,. \tag{9}$$

Taking (9) into account we determine from (8) the various energy effects on the total pressure

$$dp_* = - \rho_* v dF/f - \rho_* g dh - \rho_* (i_* - i)_s' \, ds \equiv - \rho_* v dF/f + dp_g^* + dp_{us}^* \,, \tag{10}$$

where

$$dp_g^* \equiv - \rho_* g dh \,;$$

$$dp_{us}^* \equiv \rho_* (i - i_*)_s' \, ds = \rho_* (T - T_*) \, ds = \rho_* [v_s']_{id} (p - p_*) \, ds \,; \tag{11}$$

dp_g^* is the gravity effect of p_* variation in a small portion of theflow; dp_{us}^* is the dynamic effect of a change in the flow total pressure in a small portion that is caused by the influence of heat at $[v_s']_{id}ds \neq 0$ (i.e., the effect arising at $u \neq 0$ when $p_* > p$; its negative value is known in gas dynamics as "heat resistance" [3]; by its positive value, which from a mechanical point of view is a "gain in total pressure," one can explain the observed increase in total pressure of two-phase flows in cooling [4] (usually $T_* - T > 0$ and $dp_{us}^* > 0$ when $ds < 0$, i.e., a gain in total pressure arises in cooling, (7) is taken into account in (11)). Having integrated Eqs. (1), (5), and (11) along the entire circulation flow, we find, respectively:

$$\oint dF = \oint pdf + \oint g\rho fd(-h)\,, \quad \oint vdF/f = - \oint vdp \equiv \oint pdv\,, \tag{12}$$

$$\oint \rho_* vdF/f = \oint dp_g^* + \oint dp_{us}^*\,, \tag{13}$$

where the balance identity $\oint dp_* \equiv 0$;

$$\oint dp_g^* \equiv - \oint \rho_* gdh = \oint ghd\rho_* = \oint gh\,[(\rho_p')_*\, dp_* + (\rho_s')_*\, ds] \equiv$$

$$\equiv \oint gh\,(\rho_s')_*\, ds + \oint gh\,(\rho_p')_*\,(dp_* - dp_g^*) + \oint gh\,(\rho_p')_*\, dp_g^* \tag{14}$$

is the integral gravity effect over the circular contour of the change in total pressure caused by both thermal and mechanical effects, on which, according to (10), the found difference $dp_* - dp_g^*$ depends. Under the condition

$$\left| \oint dp_g^* \right| >> \left| \oint [(gh/a_*^2)^2 + (gh\rho_*)^2 (\gamma_p')_*/2]\, dp_g^* \right| \tag{15}$$

(this inequality is expected to be valid at rather small heights), continuing transformation of (14), we express the quantity $\oint dp_g^*$ in terms of the influence of viscous friction forces, dynamic effect, and heat. Having substituted the found expression into (13), we find

$$\oint [1 + gh/a_*^2 + (gh/a_*^2)^2 + (gh\rho_*)^2 (\gamma_p')_*/2]\,\rho_* vdF/f =$$

$$= \oint dp_{gs}^* + \oint dp_{us}^* + \oint dp_{gus}^*\,, \tag{16}$$

where

$$\oint dp_{gs}^* \equiv \oint [gh\rho_*\,(\gamma_s')_*/2 + (1 + gh/a_*^2)\,(\rho_s'/\rho)_*]\,\rho_* ghds\,; \tag{17}$$

$$\oint dp_{us}^* \equiv \oint \rho_*\,(i - i_*)_s'\, ds = \oint \rho_*\,(T - T_*)\, ds\,; \tag{18}$$

$$\oint dp_{gus}^* \equiv \oint [1 + gh/a_*^2 + gha_*^2 \rho_*^2\,(\gamma_p')_*/2]\, ghdp_{us}^*/a_*^2 \tag{19}$$

are the integral, over the contour gravity, dynamic, and combined effects of the change in total pressure caused by the heat effect; dp_{us}^* (see (11)); $a \equiv \sqrt{1/\rho_p'} \equiv \sqrt{v/\gamma}$. If everywhere in the contour

$$dF > 0\,, \tag{20}$$

then Eqs. (12), (16) describe unforced convection (the strict condition (20) guarantees that no positive work is put on the circulatory flow). This convection can occur thanks to at least one of two forces (see the left-hand-side equality in (12)):

$$\oint pdf \equiv - \oint fdp > 0\,, \quad \oint g\rho fd(-h) > 0\,, \tag{21}$$

the expansion work (see the right-hand-side equality in (12))

$$\oint p dv \equiv - \oint v dp > 0 , \tag{22}$$

at least one of three effects of an increase in total pressure (see (16)):

$$\oint dp^*_{gs} > 0 , \quad \oint dp^*_{us} > 0 , \quad \oint dp^*_{gus} > 0 , \tag{23}$$

(see (17)-(19)). We emphasize that, due to two physically different factors $g \neq 0$, $u \neq 0$, according to (4) the increase in static pressure (when $gdh < 0$ and $udh < 0$) is possible that is necessary for the existence of a power source of convection (see the left-hand-side inequality in (21)) and sources in other forms (see (22), (23)), i.e., there exist two physically different mechanisms of convection – gravity and dynamic – which in (16) are represented separately by the sources (23) and together with a combined source (see (19)). Then, we consider convection mainly in terms of total pressure, because Eq. (16) explicitly allows for the effect of heat by $ds = dQ/T$ (see (17)-(19)). We note that in a simple case, when

$$1 >> |gh/a_*^2 + (gh/a_*^2)^2 + (gh\rho_*)^2 (\gamma_p')_*/2| , \quad dF > 0 , \quad \rho_* \approx \text{const} , \tag{24}$$

having divided (16) by $\rho_* \approx$ const, we obtain the equation in the form of energy, the left-hand side of this equation coincides with the left-hand side of the right-hand-side equation in (12) and, consequently, its right-hand side expresses the source of convection (22) in terms of the effects (17)-(19) (i.e., in the case of (24) we succeed in expressing the source of convection (22) in terms of heat effect $ds = dQ/T$). In a hypothetical simple case, when $\rho_s' = 0 = v_s'$, $T_* - T = 0 = \oint dp^*_{us} = \oint dp^*_{gus}$ the right-hand side of (16) takes the form

$$\oint dp^*_{gs} + \oint dp^*_{us} + \oint dp^*_{gus} = \oint dp^*_{gs} = \oint (gh\rho_*)^2 (\gamma_s')_* ds . \tag{25}$$

In the absence of the effect of heat via thermal and dynamical factors convection is possible, according to (25), due to a gravity source $\oint dp^*_{gs} > 0$ caused by the effect of heat via the factors $g \neq 0$, $\gamma_s' \neq 0$ (in a flow of an ideal gas $\gamma_s' = 0$, and this effect is absent). At $g = 0$ we obtain from (16) and the left-hand-side equality of (12) two equations, respectively:

$$\oint \rho_* v dF/f = \oint dp^*_{us} , \quad \oint dF = \oint p df , \tag{26}$$

which describe unforced convection under the condition (20) and in the absence of the effect of the fields of mass forces. In this case, the viscous friction force $\oint dF > 0$ is minimized by the pressure force $\oint pdf > 0$ (see the right-hand-side equality of (26)). We note that this force is often the only one, thanks to which unforced convection occurs under the effect of gravitation as well. For example, let, in the widely known in practice case of unforced convection in an engineering circulation contour, water with density ρ_h heated from below ascend in a wide vertical tube with diameter d_h and water with density $\rho_c > \rho_h$ cooled from above descend in a narrow vertical tube with diameter $d_c < d_h$ and let in this case the mass of the hot water filling the wide tube be greater than the mass of the cold water; this is possible if $\rho_h d_h^2 > \rho_c d_c^2$, then the total gravity force impedes the motion (the right-hand-side inequality of (21) does not hold), as does the viscous friction, and the only force causing this convection is obviously, the pressure force (see the left-hand-side inequality of (21)). If in this case velocities are small, then the pressure force $\oint pdf > 0$ is generated by the effect of heat via the gravity factor $g \neq 0$ (thus, one should distinguish between the effect of gravitation on the formation of two different force sources (21) of unforced convection). If $gdh = 0$, then the force $\oint pdf > 0$ can occur due to the efefct of heat via the dynamic factor $u \neq 0$. The theory of convection has not examined unforced motion due to the pressure force $\oint pdf > 0$ arising under the effect of heat in terms of the factor $u \neq 0$ at $gdh = 0$, though this motion is known from different branches of engineering, e.g., in the system of coordinates associated a ramjet engine uniformly and horizontally flying around the Earth, an intense circulating air flow ($u \sim 1000$) is observed that is, probably, unforced convection, since this engine has no devices that perform work over the air flow [3]; in the pipe feeding a locomotive boiler with cold water an intense motion ($u \sim 100$) is observed that occurs in the absence of external work over the flow [5]. We note that in these examples the condition $df \neq 0$, which is necessary for the existence of the force $\oint pdf > 0$, is guaranteed by the presence of a diffusor and a nozzle in the engine or injector, and the flows are cooled under nearly one-dimensional conditions, since the cooling flows of surrounding air or droplets of supply water have velocities close to the velocity of cooled flows. Thus, unforced convection occurring due to the pressure force $\oint pdf > 0$ is well know in the presence and absence of the effect of the field of mass forces. Works have recently appeared which prove, by calculations, the possibility of the existence of unforced convection in the absence of mass forces [6]. The left-hand-side equation in (26) explicitly shows this possibility, which exists due to the integral-over-contour dynamic effect of the gain in total pressure (see the right-hand-side inequality of (23)). We express this dynamic source of convection in terms of the characteristics of the medium in a simple case, when the relation $i_p' = v(p, s)$ can be presented in the form

$$v = v_0 (p_0/p)^n \exp b \equiv v_0 (p_0/p)^{n(s)} \exp b(s), \tag{27}$$

where $v_0 = v(p_0, s_0)$ is the specific volume in the reference state p_0, s_0; $b \equiv b(s) \equiv b_*$, $n \equiv n(s) \equiv n_*$ are dimensionless functions of entropy (with $b(s_0) = 0$, $0 < n < 1$). For ideal gases of molecular physics [2]: $b = (s - s_0)/c_p$, $n = c_v/c_p = \text{const} = [3/5-3/4]$, $c_p = \text{const}$. With allowance for (27), $dF = 0 = g$, $s = \text{const}$ we integrate (5) between the limits from current values i, p to i_*, p_*; as a result we have

$$i_* - i = (v_* p_* - vp)/(1 - n) = u^2/2. \tag{28}$$

Differentiating the left-hand-side equality in (28) along the flow with account for the dependences $v_* = v(p_*, s)$, $b(s)$, $n(s)$, we find for media (27)

$$(i_* - i)_s' = -(u^2/2)(\rho_s'/\rho) - (u_*^2/2)\,\Gamma(\lambda, n)(\gamma_s'/\gamma), \tag{29}$$

where

$$\Gamma(\lambda, n) \equiv [-\ln(1 - \lambda^2) - \lambda^2]\, n/(1 - n) \geq 0; \tag{30}$$

$$u_*^2 \equiv 2 v_* p_*/(1 - n) = a_*^2\, 2n/(1 - n), \quad \lambda \equiv u/u_* = [0 \div 1]; \tag{31}$$

$$\gamma \equiv \rho_p'/\rho \equiv -v_p'/v = n/p > 0, \quad \gamma_s' = n'/p, \quad \gamma_s'/\gamma = n'/n \equiv n_*'/n_*; \tag{32}$$

$$\rho_s'/\rho \equiv -v_s'/v \equiv -\beta = n' \ln(p/p_0) - b' \lesseqgtr 0; \tag{33}$$

n', b' are the derivatives of the functions $n(s)$, $b(s)$; u_* is the maximum possible velocity at the given values of retardation parameters v_*, p_*, $n_* \equiv n$ (see (28) at $pv = 0$); at the prescribed p, s the inequalities in (33) are determined by the choice of p_0 and the derivatives of the functions $n(s)$, $b(s)$. If (29) holds we obtain from (11)

$$dp_{us}^* = \rho_* (u_*^2/2)\, [\lambda^2 \rho_s'/\rho + \Gamma(\lambda, n)\gamma_s'/\gamma]\, ds = \rho_* (T - T_*)\, ds, \tag{34}$$

where $\Gamma(\lambda \neq 0, n) > 0$ (see (30)); u_*, λ (see (31)). We note that a dynamic effect of a gain in total pressure $dp_{us}^* > 0$ is possible, according to (34), due to the effect of heat that increases the density by $\rho_s' ds > 0$ and/or the coefficient of adiabatic compression by $\gamma_s' ds > 0$. Using (34) we find the integral-over-contour dynamic effect for media (27)

$$\int dp_{us}^* = \int \rho_* [u_*^2 \Gamma(\lambda, n)\gamma_s'/\gamma + u^2 \rho_s'/\rho]\, ds/2. \tag{35}$$

We note that the sources of convection (23) (and the dynamic source for media (24), se e (35), and the gravity source (see (17)) arise due to the effect of heat via two characteristics of the medium

$$\rho_s' \neq 0\,, \quad \gamma_s' \neq 0\,. \tag{36}$$

In the majority of cases both inequalities of (36) hold; for ideal gases [2]: $\rho_s' < 0$, $\gamma_s' = 0$; for a liquid phase of water: $\rho_s' > 0$, $\gamma_s' < 0$ at temperatures below 4°C and $\rho_s' = 0$, $\gamma_s' < 0$ at 4°C.

Then we study the effect of the dynamic mechanism, having assumed for simplicity and certainty, that

$$g = 0\,, \quad \gamma_s' = 0\,, \quad \rho_s'/\rho \equiv -\,v_s'/v \equiv -\,\beta < 0\,, \tag{37}$$

the velocities are small and the flow is practically incompressible ($\rho \approx \rho_*$), the values of ρ, ν, T change slightly, the thermal effect of viscosity is negligible, heat with power $\Delta N > 0$ is supplied in front of the confusor *CDA* in a wide portion at constant u_{con}, f_{con} and is removed in front of the diffusor *ABC* in a narrow portion at constant $u_{nar} > u_{con}$, $f_{nar} < f_{con}$, the force of viscous friction is determined by a simple relation

$$dF/f = [A_1\nu/(u\sqrt{f} + A_2]\rho u^2/2 > 0\,, \tag{38}$$

where $A_1 > 0$, $A_2 > 0$ are numerical coefficients that depend on the cross-section alone. Under these conditions

$$\oint dF/f = [\hat{A}_1\nu/(u_{nar}\sqrt{f_{nar}}) + \hat{A}_2]\rho u_{nar}^2/2 > 0\,, \tag{39}$$

$$\oint dp_{us}^* = \oint u^2\rho_s' ds/2 = u_{nar}^2(1 - \hat{f}_{nar}^2)\,\Delta\rho_{nar}/2\,, \quad \oint dp_{gs}^* = 0 = \oint dp_{gus}^*\,, \tag{40}$$

where $\hat{A} \equiv \oint A_1 dl/\sqrt{f} = \text{const}$, $\hat{A}_2 \equiv \oint A_2 dl/\sqrt{f} = \text{const}$ are the parameters of the contour (the reduced coefficients A_1 and A_2 in (38)); $\hat{f}_{nar} \equiv f_{nar}/f_{con} < 1$ is the geometric parameter of the contour (with this inequality the condition $df \neq 0$, which is necessary for the existence of convection due to $\oint pdf > 0$, holds); it is taken into account that $uf = u_{nar}f_{nar}$, $\nu = \text{const}$;

$$\Delta\rho_{nar}/\rho = -\,(\rho_s'/\rho)\,\Delta N/(TG) = \beta\Delta N/(TG) > 0\,; \tag{41}$$

$\Delta\rho_{nar}$ is the increase in the density of the incompressible flow caused by heat removal in front of the diffusor *ABC*. This growth of density decreases the velocities and increases the static pressures in the diffusor, thus leading to the emergence of the force $\oint pdf > 0$. Thus, in the hydraulics of incompressible flows the problem considered represents a new class of problems in which the influence of dynamic effects of the change in total and static pressures caused by the change in density due to the effect of heat is great. We note that if in front of the diffusor *ABC* the coefficient γ in a subsonic flow increased by $\gamma_s' ds > 0$, then it would also cause a decrease in velocities in the diffusor, a growth of static pressure, and the emergence of the force $\oint pdf > 0$.

Using (39), (40), and (41), we obtain from the left-hand-side equality of (26) or from (16) the dimensionless relation

$$(\hat{A}_1/\hat{u}_{nar} + \hat{A}_2)\,\hat{u}_{nar} = (1 - \hat{f}_{nar}^2)\,\hat{u}_{nar}\hat{\beta}\hat{N} > 0\,, \tag{42}$$

where $\hat{u}_{nar} \equiv \hat{u}_{nar}\sqrt{f_{nar}}/\nu$, $\hat{\beta} \equiv \rho c_v$, $\hat{N} \equiv \Delta N/(Tc_v\rho\nu\sqrt{f_{nar}})$.

Eliminating the zeroth trivial solution, we find from (42)

$$\hat{u}_{nar} = [\hat{\beta}(1 - \hat{f}_{nar}^2)\hat{N} - \hat{A}_1]/\hat{A}_2 \equiv (\hat{N}/\hat{N}_{cr} - 1)\,\hat{A}_1/\hat{A}_2 > 0\,, \tag{43}$$

where

$$\hat{N}_{cr} \equiv \hat{A}_1/[\hat{\beta}(1 - \hat{f}_{nar}^2)]\,, \tag{44}$$

is the critical power determined by the contour parameters $\hat{A}_1$, $\hat{f}_{nar}$ and the properties of the medium $\hat{\beta}$; if (43) is satisfied, we obtain from (41)

$$\Delta\rho_{nar}/\rho \equiv \hat{\beta}\,\hat{N}/\hat{u}_{nar} = \hat{\beta}\,\hat{N}\,\hat{A}_2/[\hat{A}_1\,(\hat{N}/\hat{N}_{cr} - 1)]. \quad (45)$$

It is seen from (43) that stationary dynamic convection is possible only at powers $\hat{N}$ higher than critical $\hat{N}_{cr}$ (we note that in the presence of gravitation, convection is possible also at powers smaller than $\hat{N}_{cr}$ by (44); in this case a dynamic mechanism could increase the rate of convection). Let the considered gravitationless convection take place at a power $\hat{N}$ slightly exceeding $\hat{N}_{cr}$, i.e., at $\hat{N} = \hat{N}_{cr} + \delta\hat{N}$ (where $\hat{N}_{cr} >> \delta\hat{N} > 0$) and, hence (see (43), (44)), at the velocity

$$\hat{u}_{nar} = \delta\hat{N}\,\hat{\beta}\,(1 - \hat{f}^2_{nar})/\hat{A}_2. \quad (46)$$

Then, having decreased by a small value $2\delta\hat{N} << \hat{N}$, the power becomes smaller than critical and the motion stops. The opposite is also possible – with a slight growth of power the velocity can grow considerably from a small nonzero value to a stationary one according to (46). We note that these substantial changes in velocity seem to an outside observer to be "random" processes, since they take place under practically constant conditions. When $\hat{N} >> \hat{N}_{cr}$, we obtain from (43)-(45)

$$\hat{u}_{nar} \approx \hat{N}\,\hat{\beta}\,(1 - \hat{f}^2_{nar})/\hat{A}_2^2, \quad \Delta\rho_{nar}/\rho \approx \hat{A}_2/(1 - \hat{f}^2_{nar}),$$

from which it is seen that with a practically constant increment of density, i.e., due to a mechanical mechanism, at $\hat{N} \to \infty$ the velocity $\hat{u}_{nar} \to \infty$, and higher velocities can be observed at small changes in density and temperature (this is the characteristic difference between dynamic and gravity convections). If in the laminar mode $\hat{A}_2 = 0$, then at $\hat{N} > \hat{N}_{con}$ it follows from (43) that $\hat{u}_{nar} \to \infty$, i.e., stationary convection is impossible in the laminar mode; the flow velocity will grow from a small nonzero value to the value at which the turbulent mode begins and $\hat{A}_2 \neq 0$ (this turbulization of small circulating structures in a large flow in a channel can affect the turbulent characteristics of the flow and the coefficient of heat transfer).

It follows from the above that the dynamic mechanism of convection is able to substantially diversify the behavior of an incompressible flow at a rather small effect of viscous friction forces and at a varying cross-section area, e.g., in free rotation of circular cylinders forming a circulating contour (Fig. 1); during convection in Benard cells [7] formed in a layer of mineral oil heated from below through a motionless-surface and cooled from above by air, which has virtually no retardation effect on the upper layers, where the effect of the gain in total pressure should originate; during convection in an equatorial Hadley cell in which fast-moving air flows are cooled by radiation at large heights [8]. The effect of the dynamical mechanism of convection is probably great in liquid helium, whose intense motion cannot be explained, due to the small temperature difference, by a traditional gravitational mechanism [9]; the effect is also great in convection at zero gravity, where the experimental data greatly differ from theoretical estimates of velocity without regard for the dynamical mechanism [10]; and it is high in various atmospheric phenomena (tornados, typhoons, global circulation of planetary atmospheres, etc.).

The basic results of the present theoretical study of the ways in which heat causes unforced circulatory convection under ordinary conditions (under force effect of viscosity, pressure, gravity and for a medium whose state is determined by two parameters) are the following:

1) On the basis of the Newton laws of mechanics and the first two principles of thermodynamics an effective method of analysis is suggested which describes the circulatory motion in terms of total pressure and allows for the influence of heat on the flow via the effect of entropy on enthalpy; a corresponding equation is derived in which the integral-over-contour effects (gravity, dynamic, and these combined) of the increase in total pressure that are caused by a thermal effect are sources of convection.

2) Gravity and dynamic effects of the increase in total pressure caused by a thermal effect represent two physically different mechanisms of convection: the first requires the field of external mass forces and the second requires motion; each of these mechanisms is in principle (i.e., according to the main laws of mechanics and thermodynamics) able to individually ensure unforced circulatory flow caused by a thermal effect.

3) Both the widely-known gravity mechanisms and a mechanism previously not considered in the theory dynamic mechanisms of convection arise due to a thermal effect which changes the specific volume by two ways,

direct (by thermal expansion) and indirect (by changing adiabatic compressibility) which is possible with the change in static pressure (an indirect effect of heat, e.g., due to a change in the coefficient of adiabatic compression, has been not considered by the theory as yet, though it is the only means of convection in the absence of thermal expansion).

4) The effect of the dynamic mechanism of convection increases with velocity, which greatly diversifies the behavior of an incompressible flow, causing intense motion for small changes in the rate and temperature and a "random" increase or decrease in velocity at a practically constant power of the effect of heat close to the critical value.

5) The effect of the dynamic mechanism of convection is clearly great in everywhere-occurring flows with movable surfaces of heat transfer (in this case the effect of two-dimensionality and viscous friction forces is small), which is confirmed by different observation data.

NOTATION

a, adiabatic velocity of sound, m/sec; c_p, c_v, isobaric and isochoric heat capacities, respectively, J/(kg·K); d, small increment along the flow in a small portion with length dl; F, viscous friction force, N; f, cross-section area of the flow, m^2; G, mass flow rate, kg/sec; g, strength of the field of external mass forces, m/sec; h, height, m; l, spatial coordinate reckoned along the flow, m; i, enthalpy, J/kg; dp_g^*, gravity effect of the change in total pressure, Pa; dp_{us}^*, dynamic effect of the change in total pressure caused by the effect of heat, Pa; p, p_*, thermodynamic and total pressure, respectively, Pa; Q, heat taken up by mass unit, J/kg; N, power of the effect of heat, J/sec; s, entropy, J/(kg·K); T, thermodynamic temperature, K; u, velocity, m/sec; v, specific volume, m^3/kg; $\beta \equiv v_s'/v$, entropy coefficient of isobaric volumetric expansion (the term is not generally accepted), kg·K/J; γ, coefficient of adiabatic compression, 1/Pa; ν, kinematic viscosity, m^2/sec; ρ_h, ρ_c, density of hot and cold water, respectively; d_h, d_c, diameter of vertical tubes with hot and cold water. Subscripts and superscripts: $*$ (upper), for the effects of the change in total pressure, $_*$ (lower), for the parameters of an ideally retarded flow and for maximum admissible velocity u_* at the given retardation parameters; $'$ (upper) to denote the derivative (the number of indices is equal to the order of the derivative); subscripts (in the presence of the upper $'$) denote the arguments with respect to which the derivatives are taken.

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