The phenomenon of bicyclones a high-frequency induction discharge and the related questions of flows in channels with the presence of zones of heating, bounded along the longitudinal coordinate

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Abstract. The phenomenon of a bicyclones in a high-frequency induction discharge is explained. It is shown that this phenomenon should be characteristic of a wider range of objects having an internal heat source, limited by the longitudinal coordinate. In the present work, this phenomenon is considered as peculiar to fairly wide class of flows in cylindrical channels if there are one or several heating zones (internal or external) inside these channels, limited by the longitudinal coordinate.

1. Introduction

In a series of papers [1-4] devoted to the characteristics of heat transfer and gas dynamics of a high-frequency induction plasma, in the framework of classical thermal physics a number of results concerning the gas-dynamic structure of a high-frequency induction (HFI) discharge at atmospheric pressure was obtained. In [1] the concept of fixed point of HFI discharge is introduced, where all three components of velocity of plasma gas vanish; it is also shown that it corresponds to a point on the axis of the plasmoid of HFI discharge where the value of its axial temperature is maximal at each fixed value of radial coordinate. In [3] it was found that inside the plasmoid of HFI discharge at atmospheric pressure, the areas of direct and reverse flows are separated by a surface of revolution, which is the locus of points at which the temperature of the discharge is maximum at each fixed value of the radial coordinate r. Thus, the fixed point of the high-frequency inductive discharge can be considered as a particular case of a more general physical phenomenon — the surface with zero axial velocity separating direct and reverse flows in the gas-discharge chamber of HFI plasma torch. The presence of a fixed point, drag and aft vortices in the discharge chamber of HFI plasma torch is confirmed both by the numerical results and the corresponding experimental data [5-8].

In [3-4] it was also suggested that the found phenomenon should be peculiar to a wider range of objects with internal heat source bounded along the longitudinal coordinate. In this work, this phenomenon is considered as peculiar to a rather wide class of flows in cylindrical channels in the presence in these channels of one or several zones of heating (internal or external) bounded along the longitudinal coordinate.
2. Theoretical position

Let us consider the equation describing the balance of the energy of viscous laminar flow of liquid or gas inside the cylindrical channel in the area (zone) of heating bounded along the longitudinal coordinate. In a general form it is written as follows

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q(r, z) = \rho c_p \left( v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z} \right).
\] (1)

Here \( T \) is temperature, \( \lambda \) is the coefficient of heat conductivity, \( \rho \) is the density, \( c_p \) is the specific heat capacity, \( Q(r, z) \) is the density of heat source energy put in the flow, \( v_r \) and \( v_z \) are the radial and longitudinal components of the velocity field inside the channel, respectively. It is apparent that the component \( Q(r, z) \) differs from zero only in case if heat is put in the entire channel volume, for example by RF or microwave heating, otherwise when the pipe heating is performed by heat supply to its external surface \( Q(r, z) = 0 \). From the balance equation (1), the components considering viscous heating and compressibility of medium are excluded since their value is deliberately small compared with the values provided by external heat source.

From equation (1) it may be inferred

\[
v_z(r, z) = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \lambda \frac{\partial^2 T}{\partial z^2} + Q(r, z) - \rho c_p v_r \frac{\partial T}{\partial r}
\] (2)

Now by convention consider the family of cylindrical surfaces coaxial to the channel \( \Omega \) series filling its entire internal space and complying with certain values of radial coordinate \( r \) of the channel. Due to the continuity of this coordinate there will be an infinite multitude of such surfaces, and the one that agrees with the value \( r = 0 \) degenerates to the channel axis, and the one that agrees with the value \( r = R \) coincides with its wall. At each of these additional cylindrical surfaces, we distinguish a circumference that agrees with \( \rho c_p v_r \frac{\partial T}{\partial r} \) the value of this surface bounded along the axial coordinate inside each of these heating zones, that is always possible since all heating zones are distinguished circumferences in turn form some cylindrically symmetrical surface of revolution \( \Omega_0 \), which axis coincides with the axis of cylindrical channel and that may be described by the equation

\[
\left. \frac{\partial T}{\partial z} \right|_{\Omega_0} = 0.
\] (3)

Then in accordance with the methodology [3], we determine the place of the points for which condition (3) is satisfied, that is consider the surface \( \Omega \) in the channel at which points the temperature value of radial coordinate \( r \) is maximal. At all points of the surface (3), the denominator of formula (2) vanishes, and this means that the numerator of this expression shall vanish as well since the value of longitudinal velocity \( v_z \) as a physical value everywhere should be finite. At the points of the surface \( \Omega_0 \), due to (2), it is obvious that

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \lambda \frac{\partial^2 T}{\partial z^2} + Q(r, z) - \rho c_p v_r \frac{\partial T}{\partial r} = 0
\]

from where the reverse component of velocity is

\[
v_r(r, z) = -\frac{1}{\rho c_p} \left( \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right) + \lambda \frac{\partial^2 T}{\partial z^2} + Q(r, z) \right)
\] (4)
Now come back to equation (2) and analyze the behavior of all its components at the transition through the surface \( \Omega_0 \). It is clear that at the points of surface \( \Omega_0 \), the denominator changes its sign at the passage through \( \Omega_0 \), since \( \frac{\partial T}{\partial z} > 0 \) at \( z < z(\Omega_0) \) and \( \frac{\partial T}{\partial z} < 0 \) at \( z > z(\Omega_0) \).

Neither of the numerator components, however, changes its sign at the passage through the surface \( \Omega_0 \): the components

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right), \quad Q(r, z), \quad \rho c_p v_r \frac{\partial T}{\partial r}
\]

— since they depend only on temperature and its radial (rather than axial) derivatives, and the change of transverse components of velocity because of formula (4) is small; the component \( \lambda \frac{\partial^2 T}{\partial z^2} \)

is negative both to the right and to the left from this surface; and the sign of the component

\[
\left( \frac{\partial}{\partial z} \frac{\partial T}{\partial z} \right)^2
\]

apparently determined by the sign of the derivative \( \frac{\partial \lambda}{\partial T} \) and also does not depend on the side of the surface \( \Omega_0 \) on which it is considered.

3. Results and conclusion

As we can see, zone of the components of the numerator of the formula for \( v_A(r, z) \) changes its sign when passing through the surface \( \Omega_0 \), so the numerator keeps the sign i.e., where in the vicinity of the surface, that is tends to zero on the right and left from \( \Omega_0 \) a with one and the same sign. This in turn means that the longitudinal velocity \( v_z(r, z) \) at all points be- longing to \( \Omega_0 \), changes the sign, i.e., vanishes at the points of the surface:

\[
v_z(r, z)|_{\Omega_0} = 0
\]

Physical meaning of this expression is apparently that the surface \( \Omega_0 \) is the surface separating the opposite liquid or gas flows inside the heating area (zone) bounded along the longitudinal coordinate \( z \). Further it may be shown that the surface \( \Omega_0 \), since it already exists may be only a surface.

It should be noted that close results have recently been obtained in a series of papers [9-11]. In these papers, the provisions on the formation, development, and properties of convective cumulant-dissipative structures are considered. It was shown that when a certain critical value stored in a convective medium is reached, some topologically complex 3D cumulant-dissipative structures with synergetically conjugated oppositely directed convective rotating power-mass-momentum pulses with different phase states, in particular, in tropical cyclones, with and without water vapor.

These structures of two conjugate and countercurrent cyclonic and anticyclonic flows by the external pressure profile are focused into a stable bicyclone (bicyclone FI Vysikailo). The author of [9-11] studied the energy 3D mechanism of the functioning of such a bicyclone with the help of the virial theorem. In particular, it is shown that oppositely directed flows in a conjugate bicyclone can effectively transform any internal and potential energy into rotational energy, exchanging kinetic energy, momentum and angular momentum, since they are dynamic dynamic boundaries for each other.

It is interesting to note that, as indicated in [10], the first researchers of the interferential gravitational and inertial potentials, which lead to the formation of libration points and the cumulation of the energy-mass impulse currents, are L. Euler and J. Lagrange, who discovered five libration points (cumulation) in the Sun- Jupiter. Moreover, two triangular libration points, discovered by J. Lagrange, are centers of attractors for the formation of cumulant-dissipative structures - the Trojans, the accumulation of small bodies in the orbit of Jupiter, discovered in 1906.

Thus, the result obtained by us above can also be formulated as follows. Inside the high-frequency induction discharge, which burns in air at atmospheric pressure, a stable bicyclon forms, which, due to two oppositely directed energetic mass-pulse currents, provides a zone of reduced pressure in the center of the plasmoid. In this case, the presence of a stable bicyclon results in a convective separation
of the properties of the medium in which this bicyclone exists, and thus is the decisive factor for the existence of a stable high-frequency induction discharge burning in the flow of the plasma-forming gas in the barrel of the cylindrical channel at atmospheric pressure.

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