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A new vortex method of plasma insulation and explanation of the Ranque effect

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Abstract. The efficiency of thermal insulation of a microwave-generated plasma using *reverse vortex flow* was investigated experimentally and by numerical simulations. Comparison with the conventional vortex method of plasma insulation was made. Changing the location of the vortex inlet to the exit end of the plasma torch leads to a significant decrease of the heat loss to the wall; from 30% to 5%. This result contradicts the traditional explanation of the Ranque effect. A new simple explanation of the Ranque effect of energy separation in the vortex tube is proposed. Energy separation takes place due to radial motion of turbulent micro-volumes with differing tangential velocities in the strong centrifugal field. The new model of energy separation explains such apparently mysterious phenomena as the counter-rotation of the central vortex flow layers observed in some experiments and in numerical simulations. A new approach for consideration of the confined vortex flows is described.

1. Introduction

The *vortex* method of plasma stabilization and insulation is well known. In this method the vortex generator is placed upstream relative to the electric discharge and the outlet of the plasma jet is directed to the opposite side. It is well known that a central recirculation zone of reverse flow occurs in intensive vortex streams near the swirl generator. The recirculation flow results in an upstream transfer of energy from the centre of the vortex-stabilized plasma and a significant part of this energy arrives at the plasma torch walls and becomes lost. This well-known phenomenon demands sufficient cooling of the plasma torch walls.

According to the new concept of plasma insulation [1–3] the outlet of the plasma jet is directed to the swirl generator side. In this case the plasma gas should enter the discharge zone from all sides except the outlet side and no recirculation zone should be formed.

The flow pattern in the conventional vortex unit (figure 1(a)) should be similar to that in a parallel-flow vortex tube and that in the *reverse vortex* unit (figure 1(a)) should be similar to that in the most effective counterflow vortex tube [4, 5]. So, it seems reasonable to compare the results of investigations on the efficiency of thermal insulation in the two vortex systems with theories of the Ranque effect.

2. Experiments

Experiments were performed with a microwave (MW) plasma generator with a MW power input up to 5 kW. This plasma torch is a part of an experimental set-up for treatment of inorganic salt solutions [6, 7]. A sketch of the MW plasma torch with the supposed flow patterns of gas and plasma is shown in figure 1 [2, 3]. The quartz discharge tube 1 (inner diameter 44 mm, length about 140 mm) passes perpendicularly through two waveguides (90 mm×45 mm, not shown) which supply the H_{10} mode of the MW energy (frequency 2.4 GHz) from two magnetrons. In the conventional scheme (figure 1(a)) the plasma gas (air or nitrogen) enters the discharge chamber through four inlet openings of the original tangential vortex generator 2, resulting in stabilization of the plasma 3 on the axis of the quartz tube 1 by the strong rotation of the gas. In the experimental plasma-chemical set-up [6, 7] the MW plasma torch is joined to the uncooled massive steel reactor 4 by an uncooled steel connecting cone 5.

For experiments with *reverse vortex stabilization* (figure 1(b)) an additional vortex generator 7 with a water-cooled diaphragm 6 (diameter 26 mm) was installed between the quartz tube and connecting cone. Calorimetric and electrical measurements permitted us to determine the MW power input W_p into the discharge and the heat losses W_t to the water-cooled parts of the plasma torch.

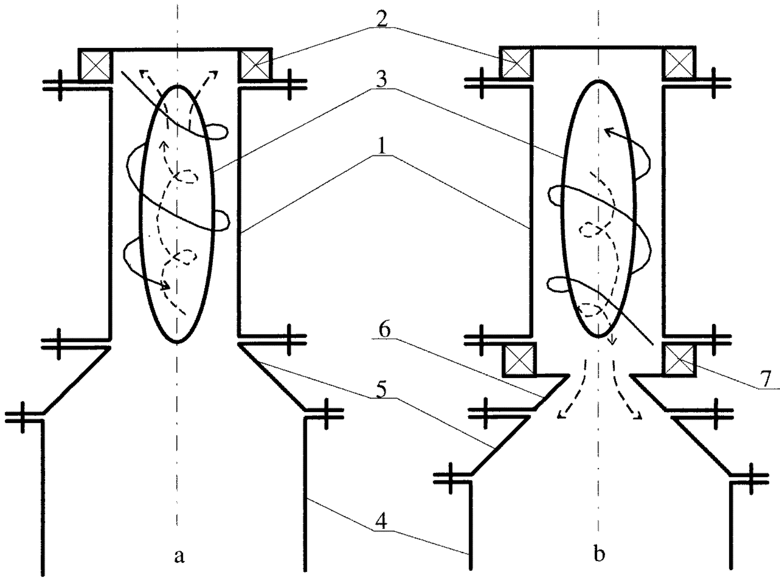

Figure 1. Schematic diagrams of the MW plasma torch with supposed flow patterns of gas and plasma: (a) the ‘old’ scheme with flow patterns for conventional vortex plasma stabilization and (b) the ‘new’ scheme with flow patterns for *reverse vortex* plasma stabilization.

Unfortunately it is not possible to use water cooling for the quartz tube of the MW plasma torch. Because this tube, however, is surrounded by the water-cooled parts of the plasma torch almost on all sides, it was supposed that practically all the heat from the quartz tube ends up in the cooling system due to convection.

The experimental results [2, 3] are presented in figure 2 (dots with full curves) in dependence on J, the energy input into the discharge per unit mass of plasma gas consumption. The power input was around 3.5 kW and varies a little due to the fact that changing the gas flow conditions also influences the discharge conditions. The dots of curve 1 were obtained for the ‘old’ scheme (figure 1(a)) *without* the diaphragm and with the plasma-chemical reactor. Curve 2 corresponds to the same scheme, but *with* the diaphragm. Curve 3 corresponds to the ‘new’ *reverse vortex flow* scheme (figure 1(b)) with the reactor. Because the heat flux to the plasma torch walls from the reactor was significant, two additional series of experiments were performed. The reactor was removed, the plasma torch was turned upside down and a hot plasma jet was directed upwards into ambient air. Because the heat losses in the ‘old’ scheme without the diaphragm were extremely large for all energy inputs, only the ‘new’ scheme (figure 1(b)) was used in the additional experiments. Plasma gas might be supplied through the original vortex generator (2, figure 1) for realizing the conventional vortex stabilization scheme or through the additional vortex chamber (7, figure 1) for realising the *reverse vortex* scheme of plasma stabilization. Curves 2′ and 3′ (figure 2) correspond to these two cases.

The experimental investigation showed that, if the plasma was stabilized by the conventional vortex flow, the energy loss to the plasma torch walls might exceed 30%. With the *reverse vortex flow* the energy loss was only about 5%. The heat loss in a simple system of this type corresponds to the low heat loss in plasma generators with a porous discharge chamber, which, however, is very complex and expensive to manufacture. Moreover, if the *reverse vortex flow* configuration is used, almost all the plasma forming gas should pass through the discharge zone. Because the axial velocity in the ‘top’ region of the *reverse vortex* should be quite low, discharge stability problems should not occur. Because the flow direction should be constant throughout the axial region, it seems possible to inject additional gas or particles into the ‘top’ of the *reverse vortex*. Tests with ZrO_2 plus Y_2O_3 powder were performed in the described MW facility. The introduction of the powder into the ‘top’ of the plasma torch with the *reverse vortex flow* plasma stabilization ensures melting and spheroidizing of particles up to 100 μm in diameter. So, the *reverse vortex* system seems very promising for various plasma-chemical processes and other technical applications utilizing microwave plasma devices as well as DC and AC plasmatrons, RF induction plasma torches and, probably, gas burners.

3. Numerical simulations

The numerical simulations of the MW plasma torch were performed using the fluid flow and heat transfer simulation program FLUENT. In the 2D axisymmetrical geometry the conservation equations for mass, energy and radial, axial and azimuthal momentum were solved simultaneously. To account for turbulence the Reynolds stress model (RSM) was used. This model involves calculation of the individual Reynolds stresses and is more suitable for rotating flows than is the usual k–ε turbulence model. For the near-wall region the program used the logarithmic law for velocity. The law of the wall for temperature in FLUENT comprises two different laws: a linear law for the thermal conduction

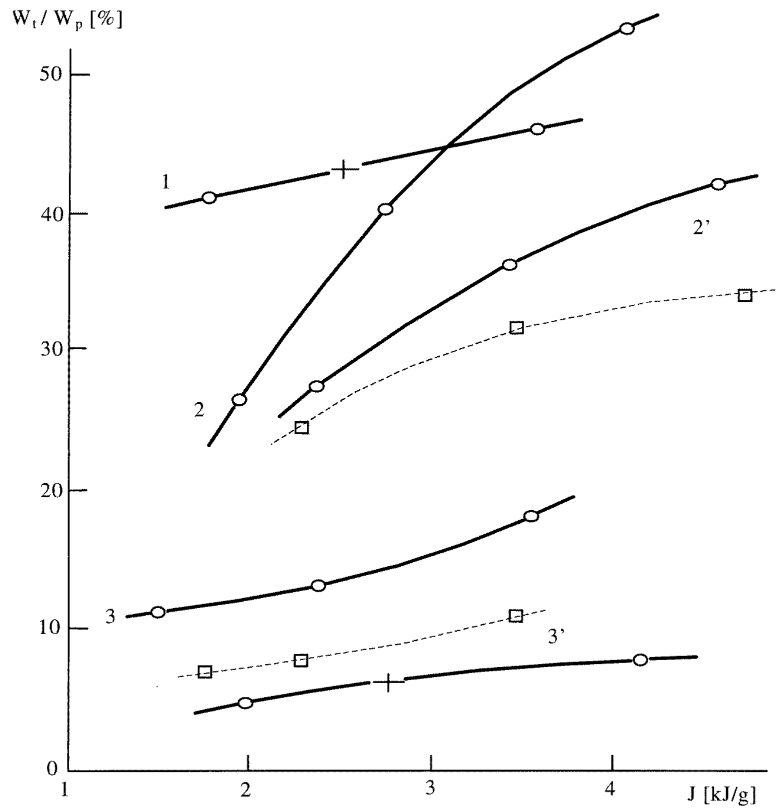

Figure 2. Heat losses in the microwave plasma generator: full curves, experiments; broken curves, numerical simulations.

sublayer and a logarithmic law for the turbulent region. The minimum size of the grid cell near the wall was about 0.3 mm. The heating of the plasma was assumed to take place in an idealized *uniform heat generation zone* in the central region of the rotating flow. The pre-described heating zone length was 120 mm. Its diameter was varied, but was usually 26 mm. The metallic parts of the plasma generator were supposed to have a constant temperature of 300 K. On the cylindrical wall convective cooling with a heat transfer coefficient of 50 W m^{-2} K^{-1} and radiative cooling with an external emissivity of 0.8 were assumed. Test calculations showed that the most realistic flow pattern in the inlet regions was obtained in a 2D geometry when the discrete tangential gas inlet jets were simulated by fixing the rotating velocity in the cells next to the cylindrical wall and defining the appropriate mass sources for the same cells.

Figure 3 shows the stream lines, contours of axial velocity and the temperature distribution for the conventional vortex scheme and figure 4 those for the 'new' *reverse vortex flow* scheme. In these two modelling cases the heating zone (3.5 kW, length 0.14 m, diameter 44 mm) was in the centre of the MW plasma torch quartz tube (1, figure 1). Gas (nitrogen) enters tangentially into the discharge chamber (conventional scheme) or into the additional vortex chamber ('new' *reverse vortex flow* scheme). The initial velocity of the tangential gas jets was estimated from the measurements of the pressure drop and the gas consumption. In the two cases showed in figures 3 and 4 the initial tangential velocities (and the gas consumption) are 100 m s^{-1} (1 g s^{-1}) and 225 m s^{-1} (1.5 g s^{-1}), respectively. It is easy to see (figure 4) that the *reverse vortex* 'compresses' the heat zone and protects the plasma torch walls from overheating. As had been supposed [1–3], the main part of the plasma gas passes through the high-temperature discharge zone and the sizes of the recirculation zones are considerably reduced. In the 'old' scheme (figure 3), on the contrary, the main part of the incoming gas mixes with the hot recirculated flow and moves along the cylindrical quartz wall, thus bypassing the discharge zone. The calculated energy losses for the appropriate cases are shown by the dots of the broken curves in figure 2 (curve 2′ is for the conventional vortex scheme and curve 3′ is for the 'new' *reverse vortex flow scheme*). A discrepancy between experimental and calculated results may occur due to the oversimplified description of the discharge zone and probably also because of experimental errors. Nevertheless, this discrepancy is small enough to allow one to conclude that the energy losses might be reliably predicted for other electric discharges and in flames by employing numerical simulation models.

Some remarks should be made about the modelling of the heating zone and the temperature field obtained. Test simulations showed that the temperature field depends only slightly on the size and shape of the heating zone. Furthermore, it is known that the maximum temperature and electron density in MW discharges is located in the centre, while the intensity of the MW field in the centre is lower due to absorption and reflection. These two factors have

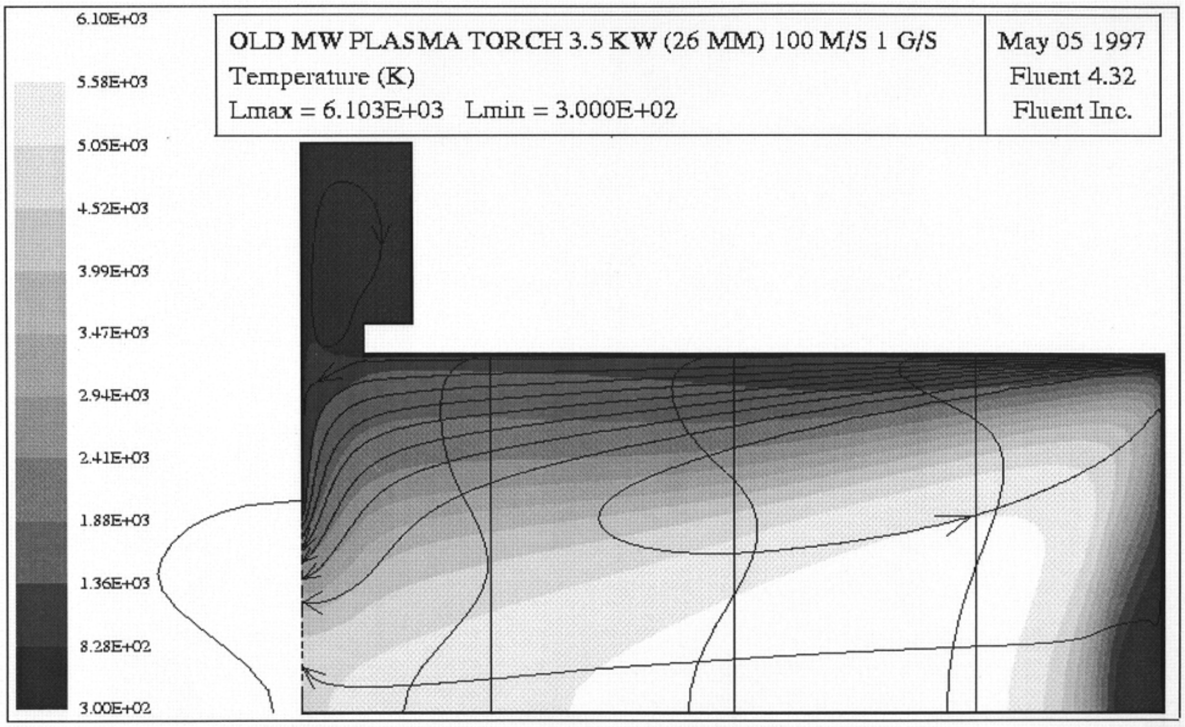

Figure 3. The temperature distribution, stream lines and contours of axial velocity for three different cross sections and for the outlet of the MW plasma torch with conventional vortex flow.

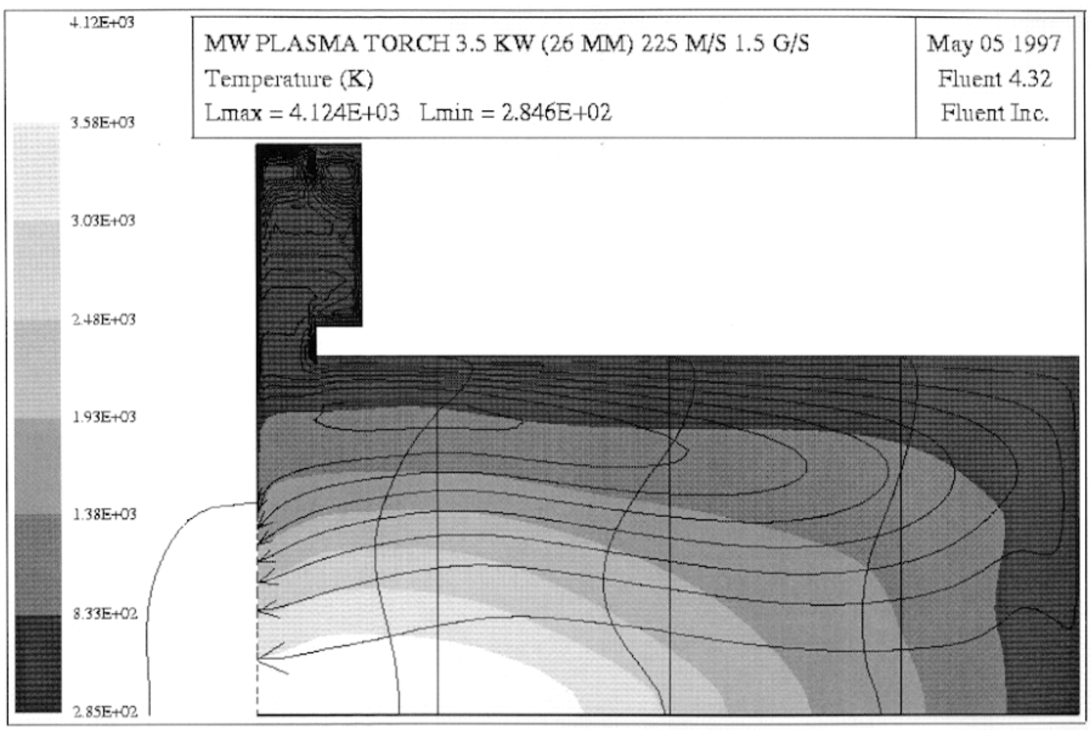

Figure 4. The temperature distribution, stream lines and contours of axial velocity for three different cross sections and for the outlet of the MW plasma torch with *reverse vortex flow*.

opposite effects on the variation of the energy generation with the radius. So, a *uniform* cylindrical heating zone is probably the most realistic one of all possible simple configurations.

Concerning the predicted maximum temperature, it is known that the gas temperature in MW discharges is usually lower than that of the electrons. The maximum gas temperature obtained for the conventional vortex scheme

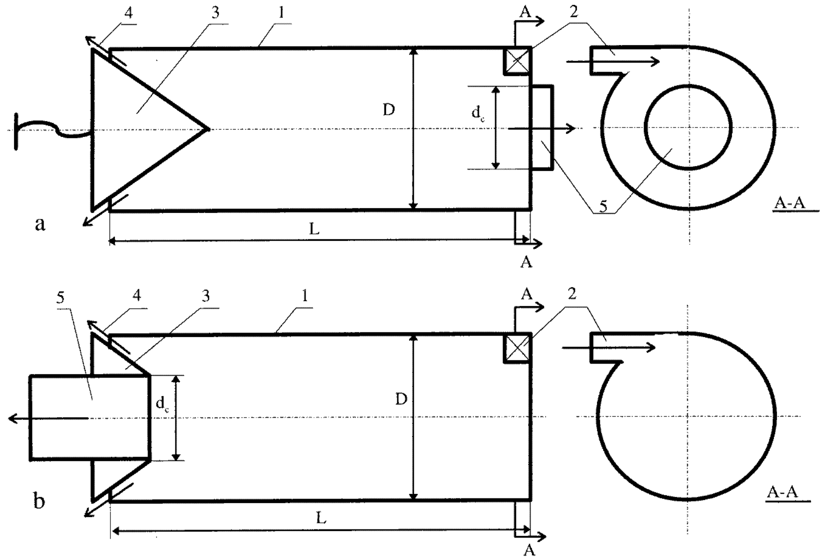

Figure 5. Schematic diagrams of the counterflow (a) and parallel-flow (b) vortex tubes.

(figure 3) is quite typical. Owing to the intensive convective cooling of the high-temperature zone in the *reverse vortex flow* scheme (figure 4), it is reasonable that the maximum temperature in this case is lower and the deviation from thermodynamic equilibrium is larger. This phenomenon may be promising for non-equilibrium plasma-chemical processes.

4. Contradiction with the traditional Ranque effect theory

The results of experiments and numerical simulations of conventional and *reverse vortex flow* systems contradict the traditional theory of the Ranque effect [4, 5]. It is worthwhile noting that modern ideas about the properties and possibilities of confined vortex flows are quite contradictory. Confined vortex flows are widely used in various devices with different, often opposite aims. For example, in vortex and cyclones combustors vortex flows improve heat exchange inside the combustor and with its walls. At the same time, in vortex plasma torches swirling flows stabilize the plasma fluid at the axis of the device and protect the torch walls from overheating. It is well known that the vortex flows are broadly used for dust separation, but at the same time it is an experimental fact that small particles with a given size concentrate at a defined radius of the vortex flow. The gas nuclear missile program, which was developed in the USA during the 1950s and 1960s, was partially based on this effect [5]. The typical high turbulence level of vortex flows is generally accepted, but in a well-known experiment [8] a combustion flame was laminarized by rotation of a cylindrical wire net screen.

All these apparently contradictory experimental data were obtained for very similar flows, only the location and method of vortex formation were different. The majority of relevant publications on vortex flows concerns technical applications. The authors of these publications were apparently not aware that their data were in contradiction with data obtained in other technical branches. Nevertheless, there is one effect, that has been known since the early 1930s as the Ranque (or vortex) effect, in which many of the contradictions mentioned above are focused. It is not difficult, however, to notice contradictions when one tries to interpret this effect, which sometimes seems rather inexplicable.

The substance of the Ranque effect is that, in technically very simple vortex devices without any moving parts (figures 5(a) for counterflow and 5(b) for parallel-flow vortex tubes), an initial isothermal gas stream, which enters the tube 1 (length L, diameter D, $L > D$) through the tangential inlet 2, divides in two flows with different temperatures: a *cold axial flow* leaves the tube through the central opening of the outlet 5 (diameter $d_c \simeq D/2$) and a *hot peripheral* one 4 through the adjustable throttle 3. This effect was established by Ranque in 1931 during an investigation of the temperature field inside a dust separation cyclone [9]. From that time until today the flow of papers attempting to explain this effect has been quite considerable. The predominant explanation [4, 5] is based on the concept of there being an intensive *turbulent* heat flux from the centre of the vortex tube to the periphery—from the cold zone to the hot one!—due to radial adiabatic motion of fluid elements in the large pressure gradient. According to this theory, inside high-speed vortex flows and, above all, inside high-speed reverse vortex flows, the radial heat flux should exist until the temperature distribution corresponds to the 'adiabatic' one. The temperature field inside the non-uniform pressure field is said to have an 'adiabatic' distribution when the temperature of the adiabatically moving test gas volumes is equal to the surrounding temperature. An approximately adiabatic temperature distribution is, for example, found in the Earth's atmosphere. So, according to the predominant theory of the Ranque effect the heat transport is almost

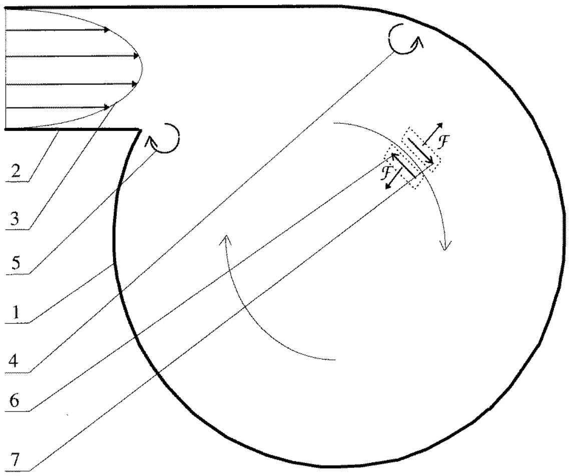

Figure 6. The proposed scheme of the energy separation in the vortex tube.

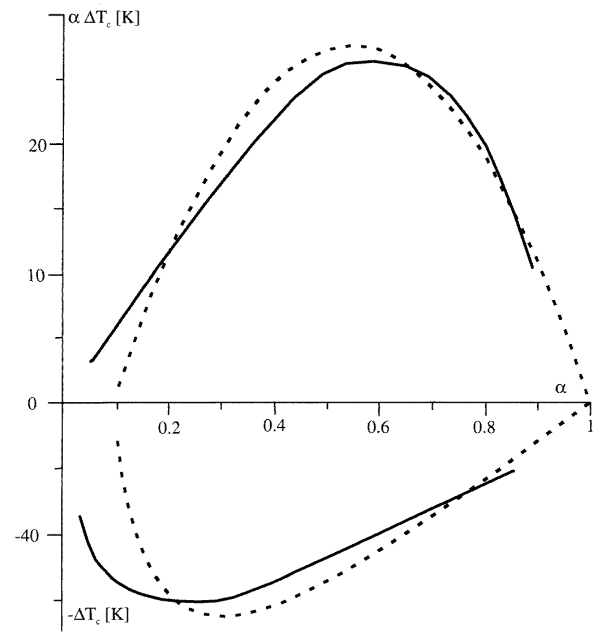

Figure 7. Characteristics of the vortex tube: full curves, experiment [6]; and broken curves, theoretical estimations based on the proposed model [9].

always directed from the centre of the vortex tube to the periphery irrespective of the temperature distribution. However, to our mind, to suppose that strong turbulence promotes such radial temperature distributions is the same as to expect that intensive mixing may promote stratification of two different liquids.

In vortex-stabilized plasma systems, the gas consumption and consequently the central pressure drop are much lower than those in vortex tubes. So in a ‘cold’ plasmatron a significant central temperature drop could not be expected and we did not try to measure this drop. Now, the estimated turbulence level should be rather high, so, according to the traditional explanation of the Ranque effect, the heat flux from the central region of a *reverse vortex flow* stabilized plasma torch should be *larger* than for a conventional vortex one, because the flow pattern in the *reverse vortex* unit is similar to that in the most effective counterflow vortex tubes.

5. A new explanation of the Ranque effect

A new simple explanation of the Ranque effect was proposed in previous works [2, 3–10]. It will be described in the following (figure 6): the initial isothermal gas stream entering through the tangential inlet 2 with a non-uniform velocity distribution 3 becomes much more turbulent during the interaction with the cylindrical wall of the tube 1 and with the main vortex flow. So, inside this turbulent rotating bulk flow, micro-volumes with different circumferential velocities, but with equal temperature, appear. It is well known that, in a centrifugal field, elements with *low* tangential velocity 6 move to the axis and elements with *high* tangential velocity 7 move to the periphery. In the coordinate system connected with the bulk rotating flow the resulting force F (figure 6) accelerates these elements in the opposite radial directions. In this way a radial separation of elements with different kinetic energies takes place. The subsequent adiabatic expansion of the central elements with low kinetic energy in the radial pressure field of the vortex flow produces the low-temperature flow. The deceleration of the peripheral high-kinetic-energy elements due to friction produces the high-temperature flow. Numerical estimations based on such a simple model [10] are in reasonably good agreement with the usual vortex tube characteristics (figure 7): the difference between initial and cold gas temperatures ΔT_c and the ‘cold capacity’ $\alpha\Delta T_c$ as a function of the mass fraction α of cold gas.

This new model explains [10] the main features of all the available experimental facts including such apparently mysterious phenomena as the counter-rotation of the central vortex flow layers observed in some experiments [11]. Figure 6 shows two main regions of formation of turbulence inside the vortex tube: a boundary layer near the cylindrical wall and an area of mixing of the bulk vortex flow with the incoming tangential flow. Turbulent micro-vortexes 5 formed in the area of mixing rotate in the same direction as the main vortex. Turbulent micro-vortexes 4 formed near the cylindrical wall (in the coordinate system connected with the bulk vortex) rotate in the opposite direction in relation to the bulk vortex. If a large number of such micro-vortexes with low mean tangential velocity and the opposite direction of rotation arrive in the central region of the main vortex, then the central region will rotate in the opposite direction.

The improved program (FLUENT with RSM and consideration of *directional diffusivity* and a non-equilibrium wall function) was used for numerical simulation of the confined *reverse vortex flow* (figure 8). In this modelling case air enters the cylindrical vessel (length 0.1 m, diameter 44 mm) through the circular slit (2.5 mm) with tangential velocity $W_0 = 100$ m s^{-1} and radial velocity 3 m s^{-1}. In figure 8 it is possible to see the negative tangential velocity W—the counter-rotating flow—near the axis of the vessel.

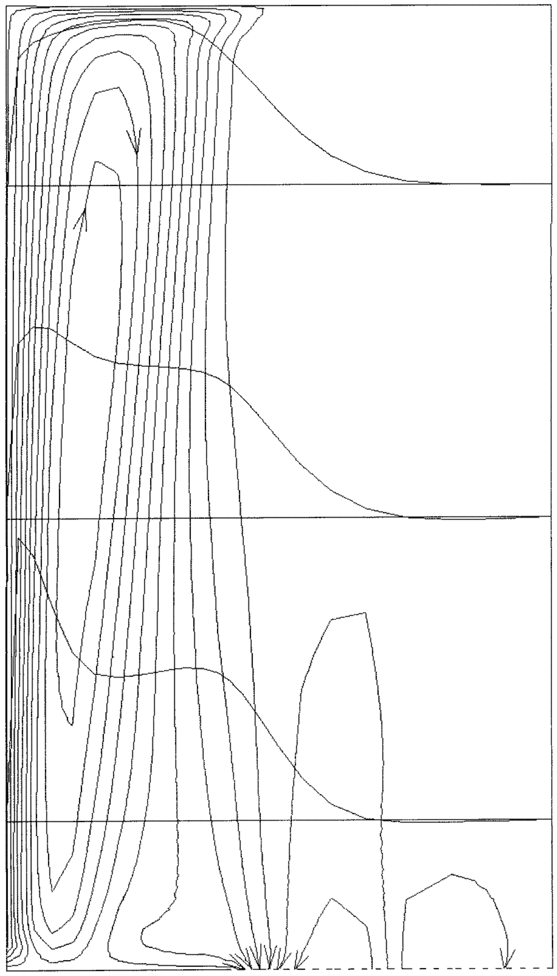

Figure 8. Stream lines and tangential velocity *W* contours for confined *reverse vortex flow*.

6. A new model for interpretation of confined vortex flows

The existence of the revised conceptual approach permits one to examine, on the basis of a unified model, all experimental results concerning confined vortex flows. The main points of this model are as follows.

(i) The *high turbulence level*, which is a characteristic feature of vortex flows, is not a product of these flows themselves. As usual, turbulence may be created in a region of vortex formation, in a boundary layer near the cylindrical wall or in an area of mixing of the vortex flow with additional incoming flows. In ordinary non-rotating flows the thickness of such regions of production of turbulence increases in the main flow direction. In vortex flows, however, there is another transport mechanism for turbulence. From the narrow regions of production of turbulence the micro-volumes with low tangential velocities move to the axis and high-velocity ones move to the periphery. Thus, the presence of these radially moving micro-volumes with tangential velocities different from the average rotational speed inside bulk vortex flow is the reason for the observed significant level of turbulence in the whole system.

(ii) The main specific features of vortex flows in various devices like those used in heat-exchange intensification and the apparently contradictory effect of laminarization of flames [8] are associated with the presence of *recirculation zones*. The number and shape of such zones (for example, see figures 3, 4 and 8) and the direction of gas circulation in them depend critically on the inlet conditions, wall roughness and system geometry. So, utilization of the usual integral characteristics of vortex flows such as *the swirl number* is often not sufficient to describe the main features of these flows, especially with counterflow geometry.

7. Discussion

It was shown that changing the location of the vortex inlet to the exit end of the plasma torch leads to a significant decrease of the heat losses. A new method of reducing the harmful influence of the reaction zone on the surrounding area and, above all, on the device walls [1] is based on such simple design modifications. The unwanted influence may, for instance, be due to the high temperature or high corrosion activity of the plasma, flame or reaction products formed in plasma generators or in combustion chambers. It may also be necessary to prevent contamination of high-purity products caused by partial melting, evaporation or dissolution of the chemical reactor walls. The basic principle of the method [1] is to locate the outlet for reaction products on the axis at the same end of the reactor as the pipe-shaped inlet for the reactants and, indeed, on the inside of this pipe-shaped inlet. When the flow direction of the products is opposite to the initial flow of the reactants then no significant recirculation zone is formed inside the reactor. This method is promising for energy saving (for example in gas-fired metallurgical furnaces, domestic gas heaters and plasma torches), for protecting the environment (laminarization of combustion should lead to less production of CO and NO_x) and for designing new simplified devices (for example, combustors of jet engines or plasma torches with uncooled walls). The new approach for consideration of confined vortex flows may give new practical results in increasing the efficiency of various 'cold' devices such as vortex tubes for gas cooling and gas separation, dust cleaning cyclones and chemical reactors.

8. Conclusion

A simple design modification of the vortex-stabilization system leads to a significant decrease of the heat flux to the walls of plasma torches (from 30% to 5% for microwave plasma). This result is in contradiction with the traditional theory of the Ranque effect, but is in good agreement with the new simple explanation of the energy separation in vortex tubes described here. Advanced numerical simulation methods permit reliable predictions of heat losses in plasma torches with conventional as well as *reverse vortex* *flow* stabilization. Experimental investigations and numerical simulations show that *reverse vortex* systems are very promising for several plasma-chemical processes and other technical applications of various plasma devices, such non-transferred arcs, RF induction and MW plasma torches, as well as for gas burners.

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