Influence of the parameters of supersonic flow on effectiveness of gazdynamic method of temperature separation

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Abstract. The process of energy (temperature) separation in an airflow is experimentally investigated in a device consisting of two coaxial channels with heat-conducting walls. The air flows at a supersonic velocity along the inner channel and at a subsonic velocity in the outer channel. The initial total temperatures of the flows are the same. Heat transfer arises due to the energy separation effect in the boundary layer of the compressible flow with Prandtl number is not equal to unity. The parameters varied in the process of investigation are the initial flow temperature, the supersonic flow velocity (Mach number), the mass fraction of the subsonic flow, the scheme of the flow organization in the device, and the presence/absence of heat transfer intensifiers in the subsonic channel. In all the regimes considered the subsonic flow cooling and the supersonic flow heating were fixed. The total pressure of the subsonic flow was almost conserved in the maximum cooling regimes. The flow parameters that have an effect on the temperature separation efficiency are determined.

1. Introduction

From the first law of thermodynamics for an open thermomechanical system it follows that the gas flow which does not execute mechanical work and takes no part in the heat transfer with the ambient medium conserves its total energy and if the perfect gas model is adopted, its total temperature also remains constant. However, this does not rule out the possibility that zones with total energies (temperatures) greater and smaller than certain initial values can arise in the flow which is repeatedly shown in the works [1-11]. The redistributions of the total energy of gas flows which do not execute mechanical work and do not take part in the heat exchange with the ambient medium, are commonly named the energy separation [6]. On the basis of some of these phenomena the devices for machine-free temperature separation of flows were developed [7-11]. The qualitative measure of the temperature separation of flows is the difference between the total mean-mass temperatures of the gas flow at the device entry and at its “hot” and “cold” exits. In other words the compressed gas with the total temperature $T_0^*$ at the device entry, having passed through it, separates into as minimum two flows, “hot” and “cold”, with the total temperatures $T_h^*>T_0^*$ and $T_c^*<T_0^*$, respectively.

A new method of the machine-free temperature separation of a gas flow was proposed and theoretically validated in [11]; the method makes it possible to considerably reduce the total pressure
loss of one of the flows. It is based on the use of the gas flow energy-separation effect in a compressible boundary layer.

A conceptual sketch of the device for realizing this effect is presented in figure 1. The compressed gas with the initial parameters $T_0^*, P_0^*$ arrives from the plenum chamber 1 in the working section, where it is divided by the partition 2 into two flows 3 and 4. Flow 3 does not undergo the geometric action and remains subsonic, whereas flow 4 accelerates in nozzle 5 up to a supersonic velocity.

![Figure 1](image)

**Figure 1.** Conceptual sketch of the device for the machine-free temperature separation (a). Total and static temperature distribution in the boundary layers of the subsonic and supersonic flows in the case of the heat-conducting dividing partition (b). For steady flow of a gas with Pr<1.

1 - plenum chamber, 2 - dividing partition, 3 - subsonic flow, 4 - supersonic flow, 5 - supersonic nozzle, 6 - supersonic diffuser

2. The state of the art

At present there are studies devoted to the numerical and analytical investigation of the temperature separation of flows on the basis of the method proposed. For example, in [11] the values of the temperature separation are estimated and the ways of increasing it are analyzed. In [12] the temperature separation in a prototype of a device consisting of two narrow plane channels separated by a heat-conducting partition is numerically investigated. The experimental results are very restricted [9, 13]. In [9] the data on the temperature decrease in the subsonic flow streaming along one of the walls of the test section of a supersonic aerodynamic setup are presented. A maximum cooling of the subsonic flow was 10.5 K, which is considerably lower than the theoretically possible maximum quantity for this method (about 36 – 38 K). In [13] the process of the temperature separation of air flows issuing from the common reservoir through a supersonic channel with the central body in the form of a copper tube was studied. The total temperature decrease at the central body exit was fixed.

Thus, at present the studies concerned with a systematic experimental investigation of the effect of the flow parameters (initial temperature, Mach number, flow pattern, mass flow rate ratio and heat transfer intensification in the subsonic flow) on the temperature separation value are lacking. In this study, the authors challenge this lack of knowledge. More information about this study can be found in [14].

3. Setup

The experimental setup is schematically represented in figure 2. The energy transfer is realized in the working section of the setup (shown by a dashed line). It consists of inner supersonic (I) and outer subsonic (II) coaxial channels. The inner channel (I) is made in the form of seven brass sections assembled together 3; each section is 100 mm in length and 29 mm in the outside diameter. In the first four sections the inner channel is conical (the conicity is 1:50). In the last three sections the inner channel is cylindrical, 14 mm in diameter. At the inner channel entry removable supersonic nozzles 2 were mounted. Altogether, three nozzles with the nominal (experimental) exit Mach numbers
corresponding to isentropic air outflow of 1.8, 2.0, and 2.5 (1.63, 1.93 and 2.3 respectively) were used. At the inner channel exit there was a supersonic diffuser of external compression 5. Having passed the diffuser, the flow found its way into receiver 10, 90 mm in the inside diameter, 300 mm in length, and 10 mm in the wall thickness. The receiver freely communicated with the atmosphere through the exit hole, 20 mm in diameter.

The outer annular channel (II) of the working section is formed by the inner surface of the steel tube 4, 32 mm in diameter, and the outside surface of the brass sections 3, 29 mm in diameter, figure 2b. The flow entry and exit was realized through steel tubes 14, 10 mm in the inside diameter, placed perpendicular to the channel axis. The plenum chamber 9 was connected with the entry tube through a 100 mm-long flexible sleeve, 14 mm in the inside diameter. Having passed the annular channel the flow arrived in the 100 mm-long ebonite receiver 11, 20 mm in the inside diameter, enclosed in a metal housing. The receiver communicated with the atmosphere through valve 12. Figure 2a presents the case in which the working section performs in accordance with the countercurrent pattern; in the concurrent pattern the plenum chamber 9 and the receiver 11 change places. In several setup operation regimes the heat transfer intensifiers in the form of annular protrusion were used. Their shapes, positions, and dimensions are given in figure 2b. All the outside surfaces of the setup are coated with heat insulator, namely, foamed polyethylene, 10 mm in thickness.

The compressed (up to 18 MPa) air was supplied to the setup from gas cylinders, 3000 m³ in the overall volume, where it arrived having passed through an oil filter and a drying system. This ensured the relative humidity not greater than 0.1% at T=300 K and P=18 MPa.

**Figure 2.** Schematics of the working section of the experimental setup. (a) - setup for investigating the temperature separation of flows and (b) - the scheme of the arrangement of the heat transfer intensifiers in the subsonic channel of the device, I – supersonic channel, II – subsonic channel 1 and 9 – plenum chambers, 2 - the removable supersonic nozzle, 3 - the brass rod with the internal conical-cylindrical channel, 4 - a tube with thermal insulation, 5 - the exhaust diffuser, 6 - pressure controllers, 7 - the flow metering device, 8 - electric heaters, 10 and 11 - receivers, 12 - valve, 13 - annular intensifiers, 14 - the entry and exit connections.

**4. Measurement and technique of investigating the temperature separation in the device**

During the experimental investigation the following parameters were fixed. The total temperatures \( T_{h1} \) and \( T_{c1} \) and pressures \( P_{h1} \) and \( P_{c1} \) in the plenum chambers 1 and 9. The flow pressure \( P_{fm1} \) and temperature \( T_{fm} \) ahead of the flow metering orifice 7, the pressure difference \( \Delta P_{fm} \) on it and pressure \( P_{fm2} \) behind of it. The probes fastened to coordinate devices measured the profiles of the total temperature \( T_{h2} \) and \( T_{c2} \) and the total pressure \( P_{c2} \) in receivers 10 and 11. The total pressure \( P_{h1} \) at the exit of the receiver of the supersonic channel was similar in value with the atmospheric pressure.

The temperature measurements were performed using chromel-alumel thermocouples. To duplicate the readings of the initial total temperatures \( T_{h1} = T_{h0} \) and \( T_{c1} = T_{c0} \) of the flows resistance thermometers with a separate digital monitor were additionally located in the plenum chambers 1 and 9. The pressure was measured using absolute and differential capacitance sensors.

Experimental investigation was devoted to the determination the temperature separation of the flows as a function of the initial flow temperatures \( T_{0} \), the Mach number at the supersonic channel entry \( M_{0} \),...
the mass fraction of the subsonic flow \(m = G_{sub}/G_{sup}\), the flow organization (countercurrent \(\uparrow \downarrow\) or concurrent \(\uparrow \uparrow\)), and the heat transfer intensification in the subsonic channel. The setup worked in accordance with the pattern shown in figure 2a. The initial parameters of the supersonic flow \((P_{h1} = P_0\) and \(T_{h1} = T_0\) for the given \(M_i\)) were set equal to those determined in the first stage. The mass air flow rate through the supersonic channel \(G_{sup}\) was not varied. The variation in \(m\) was realized by means of controlling the mass air flow rate through the subsonic channel \(G_{sub}\). For any \(m\) the temperature in the plenum chamber of the subsonic flow was set equal to that in the plenum chamber of the supersonic flow \((T_{h1} = T_{c1} = T_0\) ). The initial pressures of the flows were different only in the regimes with \(M_i = 2.5\), which was due to the specific features of the setup operation at high pressures in the plenum chamber (1.65±1.69 MPa). The main flow parameters for different setup operation regimes are given in table 1.

| № run | \(M_i\) | \(T_{h1}^*, K\) | \(T_{c1}^*, K\) | \(P_{h1}^*,\) MPa | \(P_{c1}^*,\) MPa | \(G_{sup},\) kg/s | \(G_{sub},\) kg/s range | \(m\) range | Flow org. \((\pm)\) |
|-------|--------|----------------|----------------|----------------|----------------|----------------|----------------|--------|-------------|
| 1     | 1.8    | 299.0 298.9   | 1.05 1.05     | 0.0491         | 0.00528       | -0.0369        | 0.108 - 0.752  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 2     | 299.0 298.9   | 1.05 1.06     | 0.0491         | 0.00935       | -0.0473       | 0.114 - 0.959  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 3     | 299.0 298.8   | 1.05 1.05     | 0.0491         | 0.00381       | -0.0356       | 0.078 - 0.724  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 4     | 299.2 298.8   | 1.05 1.05     | 0.0492         | 0.00452       | -0.0385       | 0.092 - 0.696  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 5     | 299.2 298.8   | 1.17 1.17     | 0.0490         | 0.00407       | -0.0388       | 0.083 - 0.718  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 6     | 2.5     | 299.1 298.8   | 1.65 1.17     | 0.0455         | 0.00398       | -0.0380       | 0.087 - 0.701  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 7     | 343.9 343.4   | 1.68 1.26     | 0.0434         | 0.00424       | -0.0311       | 0.098 - 0.716  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 8     | 313.8 313.4   | 1.68 1.25     | 0.0454         | 0.00404       | -0.0354       | 0.089 - 0.778  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 9     | 299.1 298.8   | 1.65 1.17     | 0.0455         | 0.00398       | -0.0319       | 0.087 - 0.701  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 10    | 299.0 298.9   | 1.17 1.08     | 0.0530         | 0.00431       | -0.0351       | 0.081 - 0.661  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 11    | 299.1 298.7   | 1.17 1.17     | 0.0490         | 0.00416       | 0.0349       | 0.085 - 0.712  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 12    | 299.0 298.8   | 1.17 1.17     | 0.0531         | 0.00768       | -0.0335       | 0.144 - 0.634  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |
| 13    | 314.0 313.5   | 1.20 1.20     | 0.0531         | 0.00472       | -0.0391       | 0.089 - 0.734  | \(\uparrow \downarrow\) | \(\uparrow \downarrow\) |

Simultaneously with the temperature measurements, the flow pressures were fixed at the walls of the receivers of the subsonic and supersonic flows. The pressure in the supersonic flow receiver was near-atmospheric. The pressure in the subsonic flow receiver considerably varied depending on \(P_{c1}, m\), and the presence/absence of heat transfer intensifiers in the subsonic channel. For this reason, after the temperature measurements the total pressure profiles in the subsonic channel receiver were measured at the same mass flow rates as in the temperature measurements. The values of \(P_{c1}^*\) and \(T_{c1}^*\) in the plenum channel of the subsonic flow corresponded to those in the temperature measurements. On the basis of the values thus obtained the pressure losses in the subsonic channel were determined; they included the local losses at the inlet and outlet connections. The total pressure profile at the supersonic channel exit was not measured.

5. Basic experimental results and discussion

5.1. Flow organization effect

The results are obtained for both the concurrent and countercurrent flow organizations in the device. In both cases the initial parameters of the flows are the same (see table 1, runs 1 and 2): \(P_{h1} = P_{c1} = P_0 = 1.05\) MPa, \(T_{h1} = T_{c1} = T_0 = 299\) K, and \(M_i = 1.8\). From these results it follows that the smaller the mass flow rate through the subsonic channel the greater the cooling effect. On the other hand, the greatest heating of the supersonic flow is realized at the greatest flow rates through the subsonic channel. On the parameter range considered the flow organization pattern has no appreciable effect on the flow heating (cooling).
5.2. Effect of heat transfer intensification in the subsonic flow

In figure 3a the data on the flow heating/cooling in the device and in figure 3b on the flow total-pressure loss in the subsonic flow are presented in the presence and the absence of the heat transfer intensifiers in the subsonic channel. The intensifier shapes and dimensions are shown in figure 2b. In both cases the initial parameters of the flows are the same (see table 1, runs 1 and 3): $P_{hi} = P_{ci} = P_0 = 1.05 \text{ MPa}$, $T_{hi} = T_{ci} = T_0 = 299 \text{ K}$, and $M_{i,c}=1.8$. The presence of the intensifiers leads to an increase in the cooling effect over the entire $m$ range studied; in this case the total pressure losses on the range of small $m$ remain almost invariant.

![Figure 3. Heating of the supersonic and cooling of the subsonic flows (a) and total pressure losses (b) in the presence (intensified) and the absence (smooth) of the heat transfer intensifiers in the subsonic channel as functions of the $m$ at $T_{hi}=T_{ci}=T_0=299 \text{ K}$, $P_{hi}=P_{ci}=P_0=1.05 \text{ MPa}$, and $M_{i,c}=1.8$.](image)

5.3. Supersonic flow Mach number effect

As noted above, three removable supersonic nozzles with $M_{i,c}=1.8$, 2.0, and 2.5 were used. In the subsonic channel heat transfer intensifiers were placed. The initial flow temperatures were maintained the same, $T_{hi}=T_{ci}=T_0=299 \text{ K}$ (see table 1, runs 4, 5, and 6). An increase in the initial Mach number leads to an increase in the temperature separation on the entire $m$ range. The smaller $m$ the greater the increase.

5.4. Initial temperature effect

In this case, in the supersonic channel the $M_{i,c}=2.5$ nozzle was used. The initial and regime parameters are presented in table 1 (runs 7, 8, and 9). An increase in $T_0^*$ leads to an increase in the absolute values of $\Delta T_0^*$ and $\Delta T_c^*$. The increase in $\Delta T_c^*$ in the absolute value turned out to be greater than the increase in $\Delta T_0^*$ which particularly manifested itself at the reduction in the air flow rate through the subsonic channel (decrease in $m$) (see figure 4).

![Figure 4. Relative values of the heating of the supersonic (the symbols are painted at the top) and the cooling of the subsonic (the symbols are painted at the bottom) flows as functions of the subsonic flow mass fraction $m$. The subsonic channel with the flow intensifiers](image)
6. Conclusion

The possibility of using the energy separation effect occurring in the boundary layer of a compressible gas flow for the temperature separation is experimentally investigated. For this purpose a device is developed, in which one of the flows is accelerated to a supersonic velocity, while the other flow remains subsonic. The initial temperatures of the flows are the same. As a result, the subsonic flow cooling and the supersonic flow heating was recorded. With increase in the supersonic flow cooling and the supersonic flow heating increase in the absolute value. Heat transfer enhancement in the subsonic flow leads to an increase the heating and cooling. The effect of the organization of the heat-transport medium flows is not detected. The greatest subsonic flow cooling is fixed at the least relative mass rate flows through the subsonic channel; the total pressure of the subsonic flow is almost conserved in this case. With increase in the mass fraction of the subsonic flow its cooling diminishes, the total pressure losses increase, together with the supersonic flow heating.

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