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The gas-dynamic method of energy separation (new experimental results)

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Abstract – "Energy separation" is the re-distribution of the total energy (temperature) in a fluid without external work or heat. In this paper total temperature separation of a gas flow is produced by gas-dynamic method (Leontiev's tube) proposed in [1]. A compressed air is separated geometrically into two flows by a heat-conducting material. One of the flows accelerates through the speed of sound another remains subsonic. There is a heat flux between these two flows with equal initial total temperature. As the results the rise of the total temperature of the supersonic flow and reduction one of the subsonic flow at the exit of an experimental facility with various ratio of mass flow are fixed.

1. Introduction

There are many examples of the energy separation of a gas flow [2, 3]. On the basis of the energy (temperature) separation phenomenon the machine-free techniques of energy separation of gas flows have been developed. The most widespread techniques of machine-free energy separation include the vortex and resonance methods realized in the Ranque–Hilsch vortex tubes [4] and the Hartmann–Sprenger resonance tubes [5]. In [1] a new method of the machine-free energy separation of a gas flow was proposed. The main advantage of it is that the total pressure is almost conserved for one of two flows. The basic diagram of a machine-free energy separation device realizing this method is presented in Fig. 1.

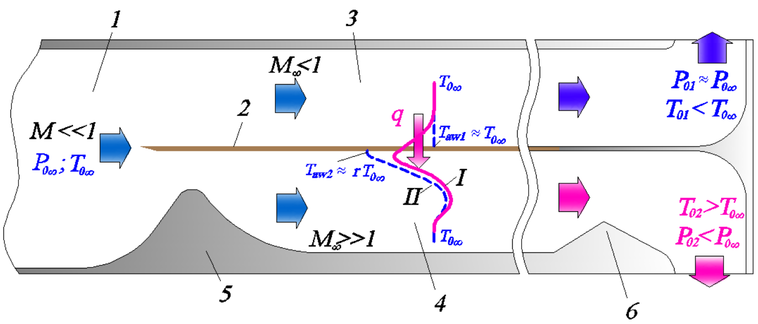

Figure 1: Basic diagram of a device for machine-free energy separation of a flow using the gas-dynamic method [1]; (1) settling chamber; (2) separating partition; (3) subsonic flow; (4) supersonic flow; (5) supersonic nozzle; and (6) supersonic diffuser. The total temperature distribution in the boundary layer in the cases of heat-conducting (I) and thermally-insulated (II) partitions

The compressed gas (air, vapor, gas mixture, etc.) supply is taken from the settling chamber 1 with the initial total parameters $T_{0\infty}$ and $P_{0\infty}$ into the working section, where it is divided by partition *2* into two flows *3* and *4*. Flow *3* is not subjected to the geometric effect and remains subsonic, while flow *4* is accelerated in nozzle *5* up to a supersonic velocity. It is known [6] that the temperature of a thermally insulated plane wall (adiabatic wall temperature) in a gas flow is determined by the expression:

$$T_{aw} = \frac{T_{0\infty}\left(1 + r\frac{(\gamma-1)}{2}\mathrm{M}_{\infty}^{2}\right)}{1 + \frac{(\gamma-1)}{2}\mathrm{M}_{\infty}^{2}} \tag{1}$$

From the approximation of the exact solution of equations of the laminar compressible gas boundary layer on a flat plate it follows that $r = \sqrt{\mathrm{Pr}}$ [22]. For the turbulent boundary layer on a flat plate $r = \sqrt[3]{\mathrm{Pr}}$. In case of the turbulent boundary layer on a flat plate and air as a working gas (Pr=0.72) $r \approx 0.9$. In the case of a subsonic flow ($\mathrm{M}_{\infty} << 1$) from Eq. (1) it follows that $T_{aw} \approx T_{0\infty}$, while in the supersonic case ($\mathrm{M}_{\infty} >> 1$) it can be taken that $T_{aw} \approx rT_{0\infty}$. In Fig. 1 the broken curve *II* presents the total temperature profiles in the boundary layers of supersonic and subsonic flows (partition 2 is a flat thermally insulated plate and $r < 1$). The partition surface temperatures on the subsonic (T_{aw1}) and supersonic (T_{aw2}) flow sides are different. Therefore, if the partition is made heat-conducting, then the heat transfer between the two flows begins. In this case, the supersonic flow is heated and the subsonic flow is cooled.
This method of total energy (temperature) separation was theoretically considered in [1, 7–11]. There are a few experimental results which are described in [3, 12-13].
The purpose of this study is to receive a new experimental data of the energy (temperature) separation process in a device realizing the gas-dynamic method described.

2. Experimental arrangement

The working section of the experimental setup is used for investigation of the gas-dynamic method of the energy separation is shown schematically in Fig. 2.

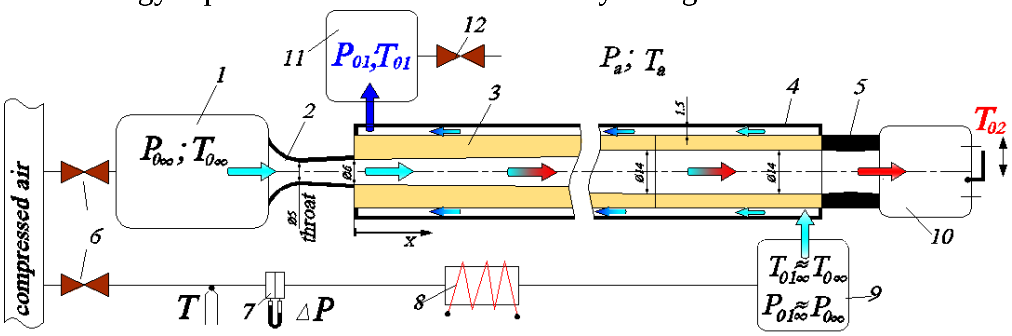

Figure 2: Diagram of the working part of the experimental setup: (1,9,10,11) settling chambers; (2) supersonic conical nozzle; (3) rod (brass) with a conical-cylindrical inner channel; (4) heat-insulated tube; (5) exit diffuser; (6) pressure regulators; (7) nozzle for mass flow measuring; (8) electric heater; (12) valve

Compressed air passing through pressure regulators *6* supplies the setup and then goes out to the atmosphere. The setup's working part consists of the supersonic and subsonic channels. The supersonic channel is formed by the axisymmetric conical supersonic nozzle *2*, the rod *3* with inner conical-cylindrical channel and the supersonic diffuser *5*. It is connected with the settling chamber *1*. The initial diameter of the conical part is 6 mm, the exit diameter is 14 mm and it length is 400 mm. The length of the cylindrical part is 300 mm and it diameter is 14 mm. Hence, the overall length of the supersonic channel which takes part in the heat transfer is 700 mm. The subsonic channel is formed by the outer surface of the rod *3* and the inner surface of a tube *4*. The subsonic channel is supplied by air from the settling chamber *9*. The initial total pressure ($P_{01\infty}$) and total temperature ($T_{01\infty}$) of the air at the settling chamber *9*

are maintained equal to the same parameters at the settling chamber *1*. The mass flow rate of the subsonic stream is determined using the pressure drop in the measuring nozzle *7*. The mass flow rate through subsonic channel is changed using the valve *12*. The mass flow rate through supersonic channel has a constant value during the experiments and is determined using the air parameters in the settling chamber *1* and the meaning of the critical nozzle area. The profiles of the total temperature at the exit of the subsonic T_{01} and supersonic T_{02} flows are measured using special probes fastened on the coordinate device in the settling chambers *10* and *11*, respectively. Also the air total pressure at the exit of the subsonic settling chamber *11* is measured. The temperature measurements are carried out using chromel-nickel thermocouples. The absolute random error in the total temperature measurements is about ±0.3 K.
The outer surface of the tube 4 and exit settling chambers are insulated with a foamed polyethylene. All measurements are conducted only after steady state has been achieved.

3. Results and discussion

The measurements of the static pressure profile along the supersonic channel were carried out before total temperature separation experiments. Also external surface temperature of the supersonic channel was measured with using an infrared scanner in the same experiment (tube *4* Fig.1 was removed and subsonic flow was absent). These data gave us the opportunity to evaluate a mean mass Mach number along the supersonic channel and the lowest temperature value of the subsonic flow (it is nearly equal to the lowest surface temperature of supersonic channel) which we could obtain in the temperature separation experiments with the same initial total parameters in the settling chambers. The initial total temperature was 298.3 ± 0.3 K, the initial total pressure - 1.05 ± 0.01 MPa. The Mach number changed from 1.7 to 2.4 along the conical part and from 2.4 to 2.1 along the cylindrical part of the supersonic channel. The lowest wall temperature was about 279.0 ± 1.0 K. Hence the maximum cooling effect for subsonic flow could be 298.3 – 279 = 19.3 ± 1.3 K. The mass flow rate through supersonic channel was $G_2 = 0.0479$ ± 0.0005 kg/s. The relative mass flow rate through subsonic channel G_1/G_2 was changed from 0.1 to nearly 1.0.

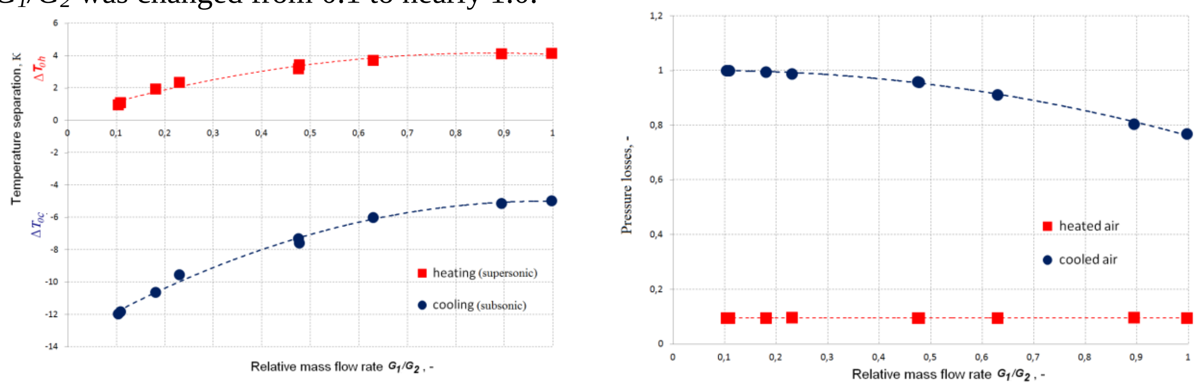

Figure 3: An absolute value of the total temperature separation (left) and the total pressure losses in the both channels (right) for different values of the relative mass flow rate through subsonic channel

Fig. 3 (left) shows an absolute value of heating of the supersonic flow $\Delta T_{0h} = T_{02}\text{-}T_{0\infty}$ and an absolute value of cooling of the subsonic flow $\Delta T_{0c} = T_{01}\text{-}T_{01\infty}$ as a function of the relative mass flow rate through subsonic channel. As can be seen the regime with lowest flow rate through subsonic channel gives a maximum temperature separation effect. It is also evident that we did not achieve the lowest cooling effect (19.3 ± 1.3 K) possible in this setup with such initial parameters. It should be noticed that T_{0i} in Fig.3 represent mean-mass temperature of a gas flow. Fig. 3 (right) represents the pressure losses in both channels which were determined as follow $P_{01} / P_{01\infty}$ for cooled air (subsonic) and $P_a / P_{0\infty}$ for heated air (supersonic). It can be seen that pressure losses for subsonic flow has small value.

4. Conclusions

The total temperature separation of the air flow was achieved using the method proposed in [1]. It is the result of the heat exchange between subsonic and supersonic streams with equal total initial parameters separated with heat-conducting partition. The subsonic stream was cooled and the supersonic one was heated. Experimental results of the temperature of the cold and hot air leaving the setup and their total pressure losses with the cold air mass ratio are presented.

Acknowledgements

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