Experimental research of shock wave processes influence on machineless gas flow energy separation effect

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Abstract. Experimental results for artificially initiated shock wave influence on machineless gas flow energy separation effect are presented. The working principle of the technique is based on interaction of supersonic and subsonic flows through the heat-conducting wall. In result at output there are two flows with different temperature – heated supersonic air flow and cooled subsonic one. Shock waves were initiated by conic ribs placed along the supersonic channel. During the research varied parameters included uni-flow and counter-flow air moving direction in subsonic and supersonic channels, subsonic flow rate divided by supersonic one (from 0 to 0.9), stagnation flow temperature (298, 313 and 343K) and initial Mach number (1.9, 2.5). The research was carried out with the use of infrared thermal imaging, thermocouples, total and static pressure probes, National Instruments automation equipment. Energy separation effect is increasing with the growth of Mach number and stagnation flow temperature. Rib placement in supersonic channel causes rise of static pressure and wall temperature and results in decreasing of energy separation effect at output of the device by less than 12%. Operability of the device with shock wave generation is remained.

1. Introduction

Machineless energy separation in fluid streams means redistribution of a gas flow enthalpy (stagnation temperature) without accomplishment of external work or heat transfer with the surroundings. Gas flow with initial temperature $T_0$ after passing through energy separation device is divided into two parts with temperatures $T_{01} < T_0$ and $T_{02} > T_0$. The most widespread energy separation devices include the vortex and the resonance tubes, energy separation in two-phase flows, pulse tubes, stratification in gas flows behind different obstacles and in a jet impingement region [1-3]. The main shortcoming of mentioned energy separation methods is high pressure losses of hot and cold flows at output of the device.

This work is devoted to another energy separation technique proposed by Alexander Leontiev [4-6]. Working principle of the device is based on thermal gas dynamic effect: adiabatic wall temperature streamlined by a compressible gas flow may considerably differ from a gas flow stagnation temperature due to the dissipative energy losses in the boundary layer (figure 1). Deviation measure is expressed by temperature recovery factor $r$ which indicates the dissipation of the flow kinetic energy. Numerous experimental researches for air flows [7] show that for a turbulent boundary layer in a supersonic air flow around the plate recovery factor $r$ lies in the range 0.885±0.010. Temperature deviation grows when applying for energy separation process different gas mixtures like helium-xenon, helium-argon, hydrogen-xenon [8, 9]. In this case temperature recovery factor is lower down to 0.3-0.4.
Compressed gas in the energy separation device is divided into two parts (figure 2). The first flow goes into supersonic nozzle and interacts with the second subsonic flow through the heat-conducting partition wall. At output there is a heated supersonic air flow and a cooled subsonic one. The performability of the device was proven by theoretical research \[8, 9\] and by experimental verification \[5, 10\].

\[ q_w = \frac{1}{\frac{1}{h_1} + \frac{\delta}{k} + \frac{1}{h_2}} \cdot (T_{aw2} - T_{aw1}) \]

For complete utilization of energy separation effect heat transfer should take place on a rather long distance. In order to increase the heat transfer rate it is necessary to rise up the less of the two heat-transfer coefficients (1). In this case it is the one at supersonic side of energy separation device. Applying any heat transfer augmentation technique (like ribs, concavities, different protrusions etc.) for supersonic channel will cause generation of shock waves \[11, 12\]. At the same time heat transfer rate is increased manifold in the shock wave boundary layer interaction region. The question is whether shock waves generation will result in operability loss of the energy separation device or on the contrary will intensify heat transfer rate resulting in a full utilization of this physical effect on reduced length.

2. Experimental apparatus, instrumentation and technique

Experiments were carried out in the energy separation device prototype \[13\]. The supersonic channel was made of brass \((k=110 \text{ W/mK})\) and included 7 parts 100 mm length each one (figure 3). The first 4 parts were conical divergent inside with opening angle 1.2º in order to keep the flow velocity constant. The last 3 parts were cylindrical in order to decrease the required flow total pressure in pipelines, on the one hand, and, on the other hand, to increase the surface area for complete energy separation effect utilization. Initial diameter of the supersonic channel was 6 mm, while subsonic circular channel internal and external diameters were 29 and 32 mm respectively. During the research varied parameters included subsonic flow rate divided by supersonic one (from 0 to 0.9), stagnation flow temperature at the inputs (298, 313 and 343 K) and Mach number in the supersonic channel (1.9 and 2.5). Mass flow rate in supersonic channel was about 45 g/sec. Shock waves were initiated by one to three conic ribs placed along the supersonic channel after the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} parts of the channel. Each rib was 1 mm length and 22º half-angled corresponding to the geometry of the previous experiments \[10, 11\]. Experiments were
carried out till ascertainment of thermal balance with the use of National Instruments equipment, LabView powered automation programs and infrared thermal imaging (Flir ThermaCAM SC-3000).

Figure 3. Experimental schematic model of counterflow energy separation device with conical ribs in supersonic channel.

The uncertainties of the main parameters were defined for 95% confidence interval [14]: Mach number ±1.2%, Reynolds number ±2.7%, wall temperature ±0.5K, flow stagnation temperature ±0.3K, stagnation pressure ±6kPa, static pressure ±0.5kPa.

3. Results and discussion

Two device configurations have been under research: “smooth channel” – supersonic flow without any disturbances and “shock wave regime with ribs”. At the first stage, a study was made of the static pressure and external wall temperature in the supersonic channel of the device (there was no subsonic flow). Within the experiment stagnation temperature in the prechamber (25.5°C and 40°C), the number of ribs (from one to three) and their location were varied.

The graph (figure 4) clearly shows the effect of the installed ribs on the dynamic characteristics of the supersonic flow. It consists in increasing of the static pressure behind the location of the rib, starting from a distance of 100 mm from the cut of the nozzle. Despite the mounted ribs due to the expansion of the supersonic channel, the flow velocity is still maintained. Thus, by means of geometric influence, it is possible to achieve the conservation of the difference in velocities between supersonic and subsonic flows.

Figure 4. Static pressure distribution along supersonic channel of energy separation device.
Installation of the ribs along the channel length increases the wall temperature (figure 5), thereby reducing the cooling potential of the subsonic flow in the energy separation device. A local increase in adiabatic wall temperature is observed before each rib. The temperature difference in the energy separation device \((T_{\infty} - T_{aw})\) decreases already at the beginning of the channel with ribs by about 3% in comparison with the smooth channel flow.

![Figure 5. Supersonic channel external wall temperature obtained with the use of infrared thermal imaging.](image)

The results of measurements of the effects of supersonic heating (figure 6) and subsonic cooling (figure 7) in the energy separation device are presented relative to the stagnation temperature at the entrance of the device. Each value of the temperature difference is represented as a function of the parameter \(\mu\), which is equal to the ratio of the subsonic flow rate to the supersonic.

As follows (figures 6 and 7) it is more efficiently to apply energy separation device for cooling. The total effect of the energy separation of the counterflow regime with ribs turned out to be greater than in the uniflow regime by up to 16.6%. A counterflow regime with a smooth channel showed the greatest effect of heating and cooling, although the difference from the ribbed channel is insignificant and, as a rule, is within the accuracy of the thermocouple readings (±0.3 K).

![Figure 6. Total energy separation effect as a function of relative mass flow rate – subsonic flow rate divided by supersonic one: heating of supersonic flow.](image)
Figure 7. Total energy separation effect as a function of relative mass flow rate – subsonic flow rate divided by supersonic one: cooling of subsonic flow.

Almost negligible influence of shock wave generation on energy separation effect is, on the one hand, a positive moment for future industrial applications of energy separation device due to absence of shock wave danger for the performability. On the other hand, such a minor influence on energy separation can be explained by insufficient rate of heat transfer augmentation in shock wave boundary layer interaction region. Energy separation effect intensification probably requires increasing of the surface area part influenced by shock waves relative to the total heat transfer area in the device.

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