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# The efficiency of one method of machineless gasdynamic temperature stratification in a gas flow

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ABSTRACT

The efficiency of a method of machineless gasdynamic energy stratification, based on heat transfer between sub- and supersonic flows separated by a thin wall, is studied numerically. A model flow consisting of two (sub- and supersonic) steady-state laminar boundary layers separated by a thin heat-conducting plate is considered. In the first part, pure-gas flows with different Mach and Prandtl numbers are investigated. In the second part, the effect of an admixture of small droplets evaporating inside the supersonic boundary layer on the efficiency of the considered energy stratification scheme is examined. The case of a thermally insulated wall between the boundary layers is also studied. It is shown that the presence of even a very low (of the order of a percent) mass concentration of evaporating liquid droplets in the supersonic stream may result in a significant increase in the difference between the average stagnation temperatures of the gases passed through the sub- and the supersonic boundary layer on both a thermally insulated and a heat-conducting plate, and hence may be a promising way to enhance the energy separation efficiency.



## 1. Introduction

In [1], a new method for machineless energy separation in a gas stream, alternative to the well-known Ranque–Hilsch vortex tube [2], is proposed. The Ranque–Hilsch vortex tube may ensure an appreciable difference in the stagnation temperatures of the outlet cold and hot streams but has a serious disadvantage associated with too large losses of the full pressure. In the scheme proposed in [1], a portion of gas entering the tube travels without swirl through a nozzle and accelerates up to a supersonic velocity. In the next section of the facility, the supersonic and subsonic gas streams having identical initial stagnation parameters move through coaxial tubes separated by a thin heat-conducting wall. Due to the heat transfer between the supersonic and the subsonic stream, the average stagnation temperatures in the outlet sub- and supersonic flows may differ by several percent, which gives the difference in the static temperatures of about several tens of degrees. The main advantage of this scheme is the assurance of low losses of the full pressure, but the efficiency of energy separation is not very high. In the scheme considered, the energy separation effect is based on the fact that, in the case of an adiabatic wall, the difference between the recovery temperatures in the sub- and the supersonic boundary layer can be quite noticeable. To illustrate this effect, in Fig. 1 we present the typical distributions of the dimensionless temperature profiles (calculated by the method described in Section 3) in the supersonic and subsonic boundary layers separated by a thermally insulated and a heat conducting flat plate. Since both these problems are self-similar, the temperature profiles are presented as the functions of the self-similar boundary-layer coordinates $y_{1,2}/x^{1/2} = (u_{1\infty,2\infty} y^{*2}_{1,2}/\nu^{*}_{1\infty,2\infty} x^{*})^{1/2}$, where $u_{1\infty,2\infty}$ are the outer (inviscid) flow velocities, $x^*$ and $y^*$ are Cartesian coordinates measured from the leading edge and normal to the plate, and $\nu^{*}_{1\infty,2\infty}$ are the kinematic viscosities of the outer flows. The stagnation parameters of both outer streams are assumed to be identical. Here and below the asterisks denote dimensional variables, where they should be distinguished from the corresponding dimensional variables. As is clear, in case of an adiabatic wall, the difference between the recovery temperatures on both sides of the wall can reach large values. In case of a heat-conducting wall, this difference is eliminated due to the heat transfer through the plate, the temperature in the supersonic boundary layer increases and in the subsonic decreases.

Since the temperature in the subsonic boundary layer changes only slightly, the heat flux through the heat-conducting wall

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**Nomenclature**

| | |
|---|---|
| $a$ | dimensionless evaporation rate |
| $c_p$ | specific heat at constant pressure |
| $\mathbf{e}_i$ | basis vectors |
| Ec | Eckert number |
| $\mathbf{f}_s$ | force acting on the particle |
| $H$ | latent heat of vaporization |
| $l_v$ | droplet velocity relaxation length |
| M | Mach number |
| $m$ | droplet mass |
| $n_s$ | droplet number concentration |
| Pr | Prandtl number |
| $p$ | pressure |
| $p_v$ | saturated vapor pressure |
| $q_s$ | heat flux to the droplet |
| $R$ | gas constant |
| $R_v$ | vapor gas constant |
| Re | Reynolds number |
| $T$ | temperature |
| $u, v$ | velocity components |
| $x, y$ | Cartesian coordinates |
| $y_{1,2}/x^{1/2}$ | dimensionless self-similar coordinates in boundary layers |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | mass concentration of droplets |
| $\gamma$ | specific heat ratio |
| $\delta$ | boundary layer thickness |
| $\varepsilon_{ij}$ | strain rate tensor components |
| $\kappa$ | coefficient in the Saffman force |
| $\lambda$ | thermal conductivity |
| $\mu, \nu$ | dynamic and kinematic viscosity |
| $\omega$ | exponent in the power law |
| $\rho$ | gas density |
| $\sigma$ | droplet radius |

*Subscripts*

| | |
|---|---|
| 0 | index of the initial stagnation temperature |
| 1, 2 | indexes of the supersonic and the subsonic flow |
| $\infty$ | free stream |
| $s$ | dispersed phase |
| $s0$ | index of the maximal droplet Reynolds number |
| $v$ | vapor |
| $w$ | wall |

*Superscripts*

| | |
|---|---|
| $*$ | dimensional parameters |
| 0 | index of particle material |
| $st$ | stagnation temperature |

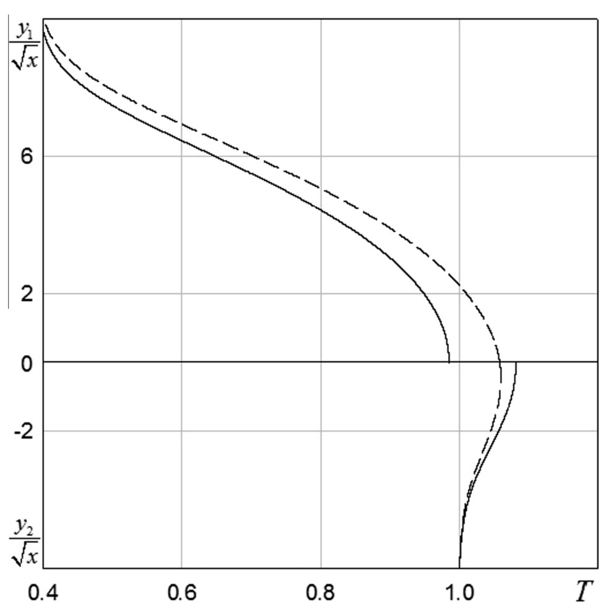


**Fig. 1.** Self-similar dimensionless temperature profiles in pure-gas boundary layers on an adiabatic (solid line) and a heat conducting (dashed line) wall. Supersonic upper boundary layer ($M_1 = 3$), subsonic lower boundary layer ($M_2 = 0.7$), $\gamma = 1.4, \mathrm{Pr} = 0.72$. Temperature is scaled to the temperature of the subsonic outer flow.

increases significantly with a decrease in the recovery temperature in the supersonic boundary layer.

The efficiency of machineless energy separation using method [1] in pure-gas flows was investigated analytically in [3,4]. In [3] an asymptotic model of two interacting self-similar boundary layers on a flat plate with different Mach numbers was considered and several limiting cases of the self-similar solution were discussed. The authors also estimated the optimum gas parameters, which ensure the maximum heat transfer across the plate, separating the sub- and the supersonic stream. In [4] the problem of energy separation in a heat exchanger, which consists of two coaxial axisymmetric tubes, is considered in a quasi-one-dimensional approximation. It is shown that the heat exchange between the streams depends strongly on the geometry of the sub- and the supersonic channel and the relative direction of the streams.

Possible ways to increase the heat fluxes through the separating wall and hence the efficiency of the energy separation, discussed in the literature, include the use of a perforated partition plate, slot or distributed injection/suction of the gas, creating a relief on the separating wall, and their combinations. Another possible way to reduce the recovery temperature in the supersonic boundary layer is to use an admixture of a liquid condensed phase, which can appear in the stream, for instance, as a result of the temperature drop caused by the gas acceleration in the supersonic nozzle.

In the present paper, we perform a parametric numerical study of the flow in two boundary layers (sub- and supersonic) separated by a thin flat wall. In the first part, we consider the heat transfer between two single-phase boundary layers and estimate the efficiency of energy separation of the gas flow with different Prandtl and Mach numbers of the streams. In the second part, using a two-fluid model of mist boundary layer we study the effect of small droplets evaporating in the supersonic stream on the recovery temperature and the efficiency of energy separation by the method considered. The calculations are performed for a wide range of similarity parameters of the gas flow and different values of the droplet mass concentration and evaporation rate.

The efficiency of energy separation will be characterized by the profiles of the dimensionless (scaled to the free stream stagnation temperature $T_0$) stagnation temperatures of the gases which pass through the sub- and the supersonic boundary layer and by the average values of the stagnation temperatures at a certain finite distance from the leading edge of the plate:

$$\langle T_i^{st} \rangle = \frac{1}{\delta_i^*} \int_0^{\delta_i^*} T_i^{st} dy^*, \quad T_i^{st} = \frac{T_i^{st*}}{T_0} \tag{1}$$

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