Journal of Applied Mechanics and Technical Physics, Vol. 38, No. 3, 1997

EFFECT OF SUPPLY OF AN INERT AND REACTIVE GAS ON SKIN FRICTION IN BODIES OF REVOLUTION

A. F. Garanin and P. K. Tret'yakov

UDC 533.601.15:536.46

The results of direct measurements of friction forces in a supersonic flow at Mach number M = 2.0 on the elements of a body of revolution with local roughness shaped as annular steps and notches are presented. It is shown that the injection of inert gases (air and hydrogen) or a reactive gas along the surface decreases considerably the skin friction. If a gas with a lower density is supplied, then a more substantial decrease in the skin friction is observed. The skin friction is reduced by 12–18% in supplying hydrogen in amounts of $\bar{G} = 0.4$–06% and by 6–10% in supplying air in amounts of $\bar{G} = 1.4$–2.4%. When the flow about the body of revolution contains $\bar{G} = 1.7\%$ of the products of incomplete burn-up of a solid propellant, the skin friction is reduced by 38%.

A special aerodynamic internal balance with semiconductor sensitive elements was designed to measure the friction forces on the elements of a body of revolution.

Gas or liquid injection to the boundary layer of various flying vehicles is of interest for purposes of heat protection and skin-friction reduction [1–4]. In a supersonic flow about bodies of revolution (such as missiles), the skin friction amounts approximately to 20% of the total drag [3]. A successful design of various flying vehicles requires their drag to be predicted. Skin-friction calculations are extremely complicated in multispecies or chemically nonequilibrium flows.

The objective of the present study is to determine how the skin friction is affected by injection of inert and reactive gases along the side surface of a body of revolution. In chemically reactive flow about the body, direct methods of measurement are preferable to indirect techniques [2].

This paper contains some results of direct skin-friction measurements of the elements of a body of revolution in supersonic flow with supply of an inert gas (air and hydrogen) or the products of incomplete burn-up of a solid propellant in amounts $\bar{G} = G\cdot 100/(\rho_\infty U_\infty F_{\rm m}) \leqslant 2.6\%$ (ρ_∞ and U_∞ are the air free-stream density and velocity, $F_{\rm m}$ is the model cross-sectional area, and G is the flow rate of the supplied gas) injected along the side surface of the body of revolution.

The experimental setup is shown in Fig. 1. The model was a body of revolution 40 mm in diameter with a conical forebody with vertex half-angle $\beta = 15°$. The skin friction was measured on the elements of revolution 1 of length $L = D$ (D is the model diameter) which are mounted on a built-in single-component balance 2 with semiconductor sensitive elements designed for the load $X = 4$ kN. The balance data were registered by a KSP-4-type automatic potentiometer and were continuously recorded prior and during the experiment. The zero (reference) data were fixed before the experiment on the model with the wind tunnel prestarted.

There was a gap $a = 0.2$–0.3 mm between the forebody and the weighed element. The forebody was not connected to the balance and was aligned coaxially with the measuring element.

The element of revolution was replaceable and had the local roughness shaped as an annular step with height $b = 0$, 0.15, and 0.5 mm or as an annular cavity (Fig. 1b). The inert gas was injected from a 4-mm-diameter pipe 4 located coaxially upstream of the model nose. In flow of burn-up products about the side surface of the element of revolution, an internal gas generator 3 was used. A pyrotechnic mixture with calorific power $H_u = 15.8$ MJ/kg was used as a fuel. The study was carried out in a wind tunnel with a

---

Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 38, No. 3, pp. 51–54, May–June, 1997. Original article submitted January 3, 1996; revision submitted January 18,1996.

0021-8944/97/3803-0374 $18.00

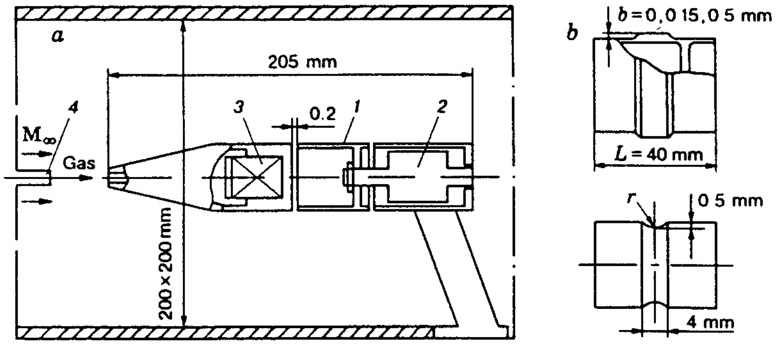

Fig. 1

Fig. 2

200 × 200 mm test section at a flow velocity corresponding to M = 2.0, static pressure P_∞ = 24–36 kPa, stagnation temperature T = 280–290 K, and Reynolds number $\mathrm{Re}_L = (2.6\text{–}4.7)\cdot 10^6$, where $L = 0.12$ m is the distance from the model nose to the element axis. The products of incomplete burn-up were ejected upstream from the model forebody and were burned up in the external flow about the model.

Figure 2 shows schlieren photographs illustrating the change in the flow structure about the model owing to the injection of inert gases and the products of incomplete burn-up. An analysis of the photographs shows that when an inert (Fig. 2b, $\bar{G} = 1\%$) or reactive (Fig. 2c, $\bar{G} = 0.6\%$) gas is injected, a much thicker boundary layer is formed around the model, as compared with the case without gas injection (Fig. 2a). When the products of incomplete burn-up are ejected upstream from the model nose, the bow shock which arises ahead of the body is detached from the model nose toward the incoming air flow.

Schlieren photographs illustrating the flow of incomplete-combustion products about the model were taken with the simultaneous use of a spark source with light-pulse duration $t = 0.5\cdot 10^{-6}$ sec and by direct flame photographing for $t = 5\cdot 10^{-3}$ sec. The noncoincident positions of the bow shock and the leading flame front are indicative of a certain variation in the flow rate of the fuel in combustion.

Calibration of the balance has shown a linear dependence of the output signal on the longitudinal load. The mean friction coefficient was calculated by the relation $C_f = X/qF_s$ (F_s is the side surface area of the element of revolution and q is the dynamic pressure of the incoming air stream).

Figure 3 shows the friction-coefficient values obtained for the elements of revolution under study. For an element of revolution with a smooth surface, C_f = 0.0020–0.0025, depending on the Reynolds number. With the step height increased from 0.15 to 0.5 mm, the value of C_f increased from 0.0035–0.0037 to 0.0063–0.0065, respectively.

Estimation of the boundary-layer thickness in the exit cross section of the element from the relation $\delta = (0.37L/D)\mathrm{Re}^{-0.2}$ [5] (L is the distance from the model nose to the end of the element of revolution) has shown that the boundary-layer thickness is $\delta = 1.2$ mm without injection of the inert gas. Injection of hydrogen in the amount $\bar{G} = 0.6\%$ increased the boundary-layer thickness up to 4.2 mm, which was determined from schlieren photographs.

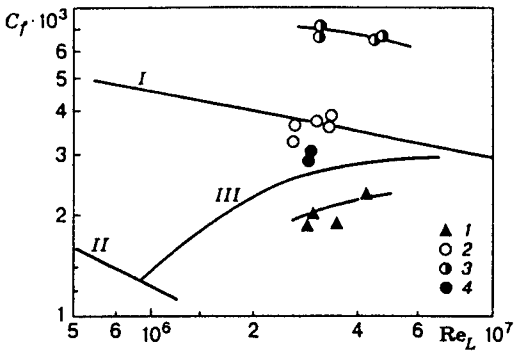

Fig. 3

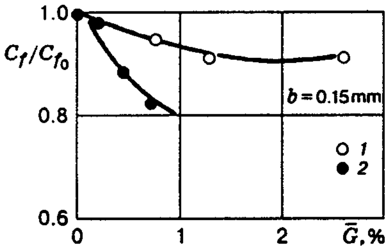

Fig. 4

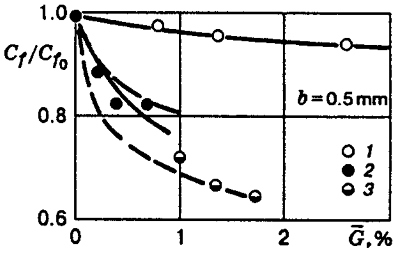

Fig. 5

To compare the C_f values obtained, Fig. 3 shows the friction coefficients C_f for a flat surface as a function of the Reynolds number and the boundary-layer state [6] (I is the curve for the turbulent boundary layer which was plotted by the formula $C_f = 0.074/\mathrm{Re}^{0.2}$ [6], II is the curve for the laminar boundary layer, and III is the mixed boundary-layer region, points 1–3 refer to $b = 0$, 0.15, and 0.5 mm, respectively, and point 4 refers to the element with a cavity). The C_f values obtained for a smooth body surface are located in the mixed boundary-layer region. In practice, supply of the inert gas along the smooth surface in the amount $\bar{G} = 2.6\%$ did not change the value of C_f. When the inert gas was injected along the surface with steps, a stable reduction of the skin friction was observed. The skin friction reduced C_f by 12–18% in supplying hydrogen in amounts of $\bar{G} = 0.4$–0.6% along the surface with the step $b = 0.15$ and 0.5 mm and by 6–10% in air supply in amounts of $\bar{G} = 1.4$–2.4% (Figs. 4 and 5). The flow with the products of incomplete burn-up of a solid propellant about the body of revolution with the step $b = 0.5$ mm leads to a larger reduction of the skin friction, as compared with the hydrogen flow, the growth of the flow rate of the fuel causing a more prominent decrease in the skin friction. In Fig. 4, the air and hydrogen injection is indicated by points 1 and 2, respectively.

When the flow about the body of revolution contains $\bar{G} = 1.7\%$ of the products of incomplete burn-up, the skin friction is reduced by 38% (see Fig. 5 where points 1 refer to air injection, points 2 refer to hydrogen injection, and points 3 refer to injection of the products of incomplete burn-up of a solid propellant).

Total-pressure measurements in the boundary layer behind the measurement element have shown that the injection of inert gases and the products of incomplete burn-up decreases the dynamic pressure and increases the subsonic boundary-layer thickness. This causes a reduction of the force acting upon the bulging elements of roughness.

Thus, one can see from this study that the injection of an inert or reactive gas along a rough surface in a supersonic flow leads to a reduction of the skin friction. If a gas with a lower density (lower molecular weight) is supplied, then a more substantial decrease in the skin friction is observed. The friction decreases owing to a reduction of the dynamic pressure acting on the roughness elements.

The balance construction which was developed allows one to perform skin-friction measurements in a supersonic flow under various actions on the state of the boundary layer.

REFERENCES

1. O. M. Kolesnikov, "Effect of hydrogen combustion in a supersonic boundary layer on the friction coefficient," *Uch. Zap. TsAGI*, **19**, No. 3, 104–109 (1988).
2. D. J. de Turris and I. A. Schetz, "Direct measurements of skin friction in a scramjet combustor," AIAA Paper No. 90-2342, New York (1990).
3. N. F. Krasnov, *Aerodynamics of Bodies of Revolution* [in Russian], Oborongiz, Moscow (1958).
4. E. D. Doss and M. G. Srinivasan, "Modeling of wall friction for multispecies solid-gas flows," *J. Fluids Eng.*, No. 4, 486–491 (1986).
5. A. I. Shvets, "Bottom flow with injection," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 5, 34–42 (1974).
6. L. G. Loitsyanskii, *Fluid Mechanics* [in Russian], Nauka, Moscow (1970).