Progress in Aerospace Sciences ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Current state and prospects of researches on the control of turbulent boundary layer by air blowing

V.I. Kornilov *

Department of Experimental Aerogasdynamics, Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya Str, 4/1, 630090 Novosibirsk, Russia

ARTICLE INFO

Article history:
Received 9 February 2015
Received in revised form
13 May 2015
Accepted 18 May 2015

Keywords:
Turbulent boundary layer
Blowing
Flow control
Skin friction and drag reduction

ABSTRACT

The paper presents the analytical review of the current state of the investigations and development trends on the problem of turbulent friction and aerodynamic drag reduction in simple model configurations, which is among key ones in modern aeromechanics. Under consideration is the modern fast progressing method of the turbulent flow control by air- and other gases (micro)blowing through a permeable surface, which is utilized in incompressible and compressible turbulent boundary layers. Several computational results to understand the essential flow physics are also included. The problem of simulation of the flow over a perforated wall where some ambiguities, in particular, at the permeable/impermeable boundary being still remained is discussed. Special attention is paid to the analysis of most important experimental and numerical results obtained with the air blowing through a finely-perforated surface, analysis of the physical peculiarities and regularities of the flow with the blowing, probability to describe the properties of such a flow within simple approach frameworks, evaluation of the efficiency of this control method, as well as the trends and opportunities of this method progress in view of state-of-the-art achievements. Although this technology has a penalty for developing the effective turbulent-flow control method, some modifications of the air blowing are an attractive alternative for real applications.

Contents

1. Introduction

Over the last approximately three decades, the interest was substantially intensified in finding new energy-conserving means

* Corresponding author. Fax: +7 383 3307268, kornilov@itam.nsc.ru.

http://dx.doi.org/10.1016/j.paerosci.2015.05.001
0376-0421/

Please cite this article as: V.I. Kornilov, Current state and prospects of researches on the control of turbulent boundary layer by air blowing, Progress in Aerospace Sciences (2015), http://dx.doi.org/10.1016/j.paerosci.2015.05.001

Nomenclature

B	normalized average (in area) blowing coefficient, $2C_b/C_{f0}$
C_b	average (in area) blowing coefficient, $\rho_b U_b/\rho_\infty U_\infty$
C_F	streamwise average skin-friction coefficient, $F/0.5\rho_\infty {U_\infty}^2 S$
C_f	local skin-friction coefficient, $\tau_w/0.5\rho_\infty {U_\infty}^2$
C_x	total drag coefficient, $X/0.5\rho_\infty {U_\infty}^2 S$
G	Clauser equilibrium parameter, $\sqrt{2/C_f}\,(H-1)/H$
H	boundary-layer shape factor, $H=\delta^*/\delta^{**}$
q	dynamic pressure, $0.5\rho_\infty {U_\infty}^2$
Re_x	Reynolds number based on U_∞ and x
Re^{**}	Reynolds number based on U_∞ and δ^{**}
U	freestream velocity, m/s
u^+	law-of-the-wall coordinate, u/υ_*
u'	streamwise velocity fluctuation, m/s
υ_b	blowing air velocity, m/s
υ_*	friction velocity, $\sqrt{\tau_w/\rho_w}$, m/s
y	wall-normal coordinate, distance from wall, mm
y^+	law-of-the-wall coordinate, $y\upsilon_*/\nu$
δ_{99}	boundary-layer 99% thickness, mm
δ^*	boundary-layer displacement thickness, mm
δ^{**}	boundary-layer momentum thickness, mm
ν	kinematic viscosity
ρ	density
τ_w	wall shear stress, kg/m^2

Subscripts

av	average
b	blowing conditions
max	maximum
w	wall conditions
0	total pressure conditions, with no blowing
∞	freestream conditions

Superscripts

'	fluctuating quantity
+	wall unit quantity.

of shear-flow control to reduce the drag and aerodynamic forces affecting moving objects, such as aircrafts, ships, submarines, and torpedoes. Repeated attempts were undertaken to study the applicability of different passive and active methods of action on the turbulent boundary layer, including all sorts of vibrators, actuators, microelectromechanical systems (MEMS), polymer additives, gas microbubbles, surfactants, riblets, large eddy breakup devices (LEBU), etc. (see e.g., [1–3]). Among other possible approaches, one can mention the suction from the boundary layer or blowing, blowing/suction, and injection of gases with various viscosities and/or temperatures.

The keen interest in this area is commonsensical and rises from the fact that the drag reduction is one of the encouraging directions to improve the aerodynamic efficiency of transportation. As a consequence, this makes it possible to enlarge the transportation range and payload, reduce fuel consumption, and impact the operating cost of a vehicle, e.g. of an aircraft. Indeed, according to estimations, just 1% drag reduction of an aircraft such as the A340-300 can save about 400,000 l of fuel per year. On the other hand existing data [4] indicate that in recent years, all transportation systems in the United States spend up to 25% of the energy consumed to overcome the aerodynamic drag. Only ground vehicles spend in such a way 27% of the total energy. The real-life estimations show that the application of prospective technologies to reduce the drag of the ground vehicles can provide an annual economy of about 20 billion dollars only in the United States alone.

One more practical challenge should not be left unmentioned, namely the thermal protection of the surfaces under the action of high-enthalpy flows (gas turbine blades, combustion chamber walls and other elements of a rocket engine), because this process involves the blowing (fluid injection) through a porous wall [5–10]. This method permits controlling the wall temperature and keeping it within labor safety limits. The methods of thermal protection of the tested wall with gas screens are also widely used in current technology. The basic challenges of mass transfer and methods of thermal protection of the tested wall are discussed in Refs. [11,12], where several issues of the efficiency of such approaches are summarized. This problem requires special consideration and is omitted here.

In addition to the above, note that application of effective methods of the turbulent friction reduction is of high practical importance not only for transportation systems but also for main gaslines, petrol, products and water pipelines; thanks to an appropriate engineering solution, many millions of national resources can be saved in this area.

Consideration of all sorts of available methods and approaches to the friction reduction is beyond the vision of this paper; this would be a topic for a special detailed analysis. Interested readers are advised to reach for the materials of Refs. [1–3,13,14]. Here we just note that there is one method which apparently was not properly evaluated and logically concluded; it is the gas injection or blowing into a turbulent boundary layer. Many researchers supposed that the energy consumptions of this process would be too high. This method is based on the concept that during the blowing process, the gas or fluid mass moves, e.g., through a slot or a orifice normally or tangentially toward the surface, and the velocity of the initial flow near the wall in a certain area downstream can be reduced, which in turn reduces the skin friction. In particular, it is possible to approach to the separation flow mode with the low skin friction, or prevent flow separation via controlling the blowing velocity and free stream velocity relation.

The emphasis in recent years has shifted to the active flow control. This method is based on a system responding to certain actions, on a system with feedback, or on an adaptive system, which is the most comprehensive one. Nevertheless, the passive methods, to which the control by blowing can be attributed, have not exhausted their significance because their application does not require much energy inputs to reach the effect of drag reduction. These methods are referred "passive" because they have no feedback for finding and manipulating the structures that have to be controlled. Therefore, such control methods, including air blowing, are much less expensive than the active ones.

A succession of experimental and computational studies during some decades was focused on this topic. Main issues of drag reduction by gas blowing are considered in Section 2. Although recent advances in computational tools have played an important role, these are not the main focus of the paper. At once some importance of numerical methods is given in the context of skin friction prediction. Concerning experiment, the classical preferred approach, suitable for engineering purposes, as a rule, was used for parametric studies whose results were then assimilated into some empirical correlations. Therefore, the primary emphasis of this

Please cite this article as: V.I. Kornilov, Current state and prospects of researches on the control of turbulent boundary layer by air blowing, Progress in Aerospace Sciences (2015), http://dx.doi.org/10.1016/j.paerosci.2015.05.001