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On the bursting condition for transitional separation bubbles

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ABSTRACT

The reattachment region in a transitional, separated boundary layer has been experimentally investigated using non-intrusive, laser based flow diagnostics. The separated flow is generated over a flat plate that is subject to an externally imposed adverse pressure gradient. After boundary layer separation, the resulting shear layer undergoes transition and it may reattach to form a closed recirculation bubble. Particle Image Velocimetry measurements are used to obtain a detailed description of the separated flow region. Subcritical and supercritical reattachment regimes, respectively characterized by short and long recirculation bubbles, are found to depend on the Reynolds number based on the maximum edge velocity and on the pressure gradient characteristic length. Previously reported criteria are explored to describe the value of the critical Reynolds number limiting the two flow configurations. Detailed measurements are conducted to describe phenomenological differences between the two flow regimes. Based on these descriptions, a simplified model is proposed to estimate the critical Reynolds number, showing that it is able to provide appropriate scaling of this parameter.

1. Introduction

Transitional separation bubbles (TSBs) are frequently found in aeronautical applications. Their prevalence is related to the response of laminar boundary layers developing in adverse pressure gradients [13]. Provided that the Reynolds number is low enough to avoid flow transition upstream of the adverse-pressure-gradient region, the scenario is propitious for the generation of a separation bubble. This occurs, for example, on the suction side of unmanned air vehicles wings [15], wind turbine blades [18], or modern aero-engine low pressure turbine blades [12].

The flow development after the laminar separation station depends strongly on the behavior of the separated laminar shear layer. Classical description of TSBs based on previous studies is shown in Fig. 1. As a result of the highly unstable character of shear layers [5,13], kinetic energy is transferred from the mean separated flow to instability waves. These waves are amplified in the separated shear layer and trigger the transition process [22]. In the final stages of this sequence, the momentum transfer taking place at the region close to the wall increases, causing reattachment of the separated, turbulent shear layer [21]. A recirculation bubble of low momentum fluid enclosed between the separation and the reattachment stations is then formed.

TSBs can be classified as short or long bubbles. The difference between the two types is controversial and difficult to define in a universal sense, due to the wide variety of laminar flow separation scenarios (airfoils, backward facing steps, induced separation bubbles over flat plates, etc.). In early studies over airfoils, Tani [23] considered that a long bubble causes a global effect on the pressure distribution over the airfoil surface, whereas the effects of short bubbles are limited to a local region. Gaster [6], from pressure and hot-wire measurements performed on a flat surface for different Reynolds numbers and pressure gradients, found no remarkable differences between the two bubble types up to the location of transition. The distance of the mixing process prior to reattachment appeared to be responsible for the observed differences in the pressure distributions between short and long bubbles. The latter are characterized by a slower and smoother recovery of the mean wall pressure distribution towards the inviscid profile. More modern studies have found that there is an inherent unsteady behavior related to TSBs due to the formation of well-defined vortical structures in the rear region of the bubble that are convected downstream [2,17,19,21]. These structures, depending on the flow conditions, can persist for a relatively long distance downstream of the mean reattachment point [19], or disappear shortly after reattachment is completed [21].

An important aspect related to TSBs is the occurrence at given flow conditions of the so-called "bubble bursting" events, characterized by a rapid switch between short and long bubble configurations. In early studies, bubble bursting was interpreted as

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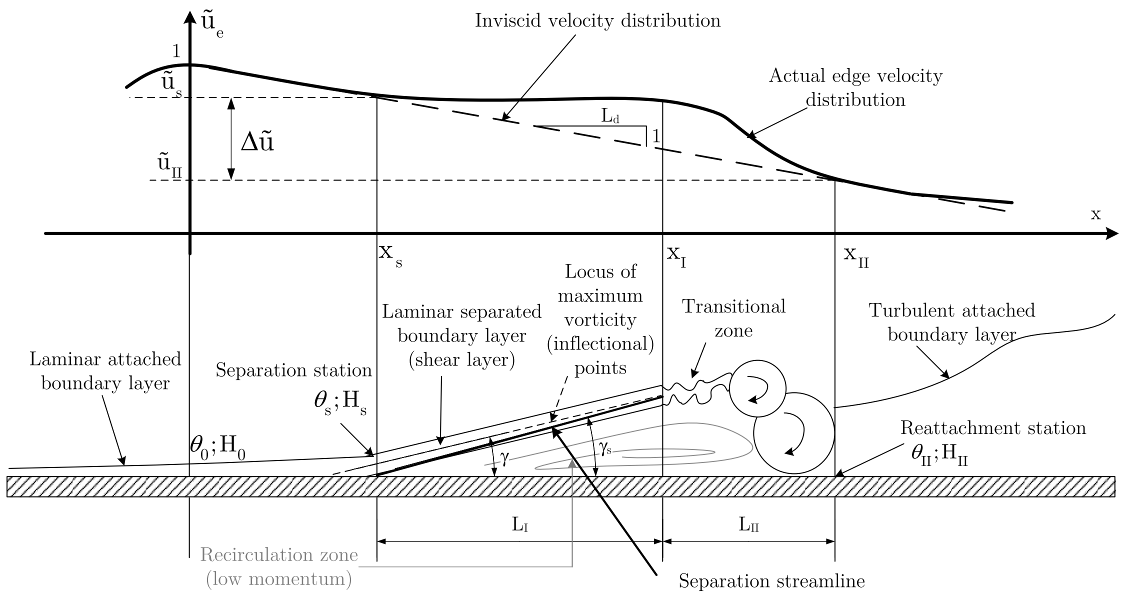

Fig. 1. Transitional separation bubble. Sketch and nomenclature.

the inability of the turbulent shear layer to reattach [23]. Nevertheless, it can also be interpreted as the momentary breakdown of the turbulent shear layer reattachment process, which results in the sudden switch between short and long bubbles. Not only the knowledge of the flow physics underlying the bursting phenomenon, but also the derivation of simple laws to predict these events have been recurrent concerns in TSBs' research. This attention is motivated by the large impact of the bursting events on the performance of aeronautical airfoils, mainly related to their stall behavior [7,23].

The most extended bursting criterion is found in Gaster's work [6]. Defining the momentum thickness Reynolds number at separation as $Re_{\theta s} = \frac{\theta_s u_s}{\nu}$, where u_s is the boundary layer edge velocity at the separation station and θ_s the momentum thickness at that position, Gaster's criterion is formulated around a relationship between $Re_{\theta s}$ and a parameter P_G related to the imposed inviscid, adverse-pressure-gradient:

$$P_G = \frac{\theta_s^2}{\nu}\left(\frac{\Delta u}{\Delta x}\right)_{inv} \quad (1)$$

with Δu denoting the change in edge velocity over the length of the bubble if the edge velocity at reattachment coincides with the inviscid velocity at that station, and Δx representing the bubble length. According to Gaster, there is a critical value of this parameter, $P_G^\star$, which depends on the Reynolds number at separation $Re_{\theta s}$, such that bubble bursting occurs when the following condition is met:

$$P_G < P_G^\star(Re_{\theta s}) \quad (2)$$

Another bursting criterion is due to Pauley et al. [20]. Based on numerical simulations of laminar separation bubbles, they proposed an alternative bursting parameter:

$$P_P = \frac{\theta_s^2}{\nu}\left(\frac{du_e}{dx}\right)_{\max} \quad (3)$$

with $(\frac{du_e}{dx})_{\max}$ being the maximum value of the separated shear layer deceleration. They also characterized the bursting phenomena as the breakdown of an unsteady separation due to periodic vortex shedding, although in their study there was no transition from laminar to turbulent flow and therefore they didn't consider realistic TSBs. In their approach bursting occurs when this parameter falls below a certain threshold $P_P^\star$:

$$P_P < P_P^\star \approx -0.24 \quad (4)$$

Long and short TSBs, and the bursting criterion have been experimentally studied by Hatman and Wang [10]. In this work, the transition is always triggered by the breakdown of Kelvin–Helmholtz (KH) waves. For the short bubble case, the process results in vorticity ejection by the periodic shedding of a large vortex blob. For the long bubble case, there is no vortex shedding and the KH waves develop into an oscillating, near-wall stagnant fluid cell with several reattachment points. These authors summarize their findings in [11], where they propose $Re_{\theta s} < Re_{\theta s}^\star = 240$ as the bursting criterion. No physical justification of this value is given, although it is very similar to the one suggested by Houtermans [14], being $Re_{\theta s} < Re_{\theta s}^\star = 220$.

The work of Diwan et al. [4] criticizes the Gaster's criterion because it fails to be universal. In this study a new criterion is proposed based on the height of the bubble, arguing that non-linear mechanisms of the transitional process appear at this height. Thus, an alternative bursting parameter is proposed:

$$P_D = \frac{h^2}{\nu}\left(\frac{\Delta u}{\Delta x}\right)_{act} \quad (5)$$

where h denotes the height of the bubble and the velocity gradient is calculated from the actual rather than from the inviscid velocity distribution. The bursting condition for these authors becomes $P_D < P_D^\star = -28$. An in-depth reasoning for this criterion can be found in [3], where the bursting condition is linked to the relative position between the location characterizing the inflectional point in the separated shear layer velocity profiles, y_{in}, and the height of the separation streamline y_d, defined as the distance to the wall that gives zero net flow at each downstream location. After analyzing the shapes of two-dimensional instability modes, it is concluded that a necessary condition for bursting is $y_{in} < y_d$.

The present work tries to shed light on the bursting condition that characterizes TSBs generated over a flat plate with an adverse pressure gradient. Section 2 describes the experimental setup and the measurement technique used in this study. In Section 3, experimental data are used to evaluate the existing bursting criteria. Additionally, they are compared with other values found in literature. Finally, an alternative new bursting criterion is proposed