1 Introduction

In 2019, the worldwide air traffic was doubling every 15 years and market forecasts were maintaining these trends for the next 15 years to come (Airbus 2013). Between 2007 and 2016, the air freight tonnage increased by 27.7 %, while the passenger traffic increased by 51 % (Berster et al. 2016, Airbus 2019). Towards the end of the year, this market was dramatically impacted by the COVID-19 pandemic. According to the International Civil Aviation Organization (ICAO), the governmental containment measures due to the pandemic led to a reduction of 43–48 % of the total number of world passengers in 2021 compared to 2019 (ICAO 2021). Nevertheless, the growth of this market remains sustained by the strong wish people place in travelling for business or pleasure and the further development of air freight. Consequently, the ICAO predicts a return to 2019 Revenue Passenger-Kilometres already by 2023 (optimistic scenario) due to the early availability of vaccines.

In this context of exacerbated competition, both the economic efficiency optimization of this growing market and the pressure for environmentally friendly technologies exert a tremendous pressure on the industry players. This pressure shapes the market towards reduced specific fuel consumption (SFC) engines and corresponding lower gaseous and smoke emissions. This target becomes all the more so important that the environmental regulations from the ICAO were expected to become significantly more drastic with the goal of increasing fuel efficiency by 2 % per year and carbon-neutral growth from 2020 onwards (ICAO 2018).

Thanks to their high-power density and high thermal efficiency compared to other engine types, gas turbines have become a key technology in both air transport and electric production. Modern aero-engines reach a thermal efficiency of more than 48 % by pushing their compressor pressure ratio up to 45 and the turbine inlet temperature up to 1,700°C (Ballal and Zelina 2004). The performances of an aero-engine are usually described by two parameters: the SFC, defined as the fuel consumption per unit thrust, and the specific thrust, defined as the thrust per unit mass flow of air. Several parameters affecting the SFC and the specific thrust for a turbofan have been identified by Saravanamuttoo et al. (2009): by-pass ratio, compressor pressure ratio, or turbine inlet temperature, to mention just a few of them. The propulsive efficiency of modern aero-engines has been significantly improved by increasing the by-pass ratio of the engine by a factor of nine between 1960 and 2005 (Ballal and Zelina 2004). However, a higher by-pass ratio reduces the specific thrust, while an increased compressor pressure ratio leads to a reduced SFC. Further increase in by-pass ratio is also limited by the aircraft infrastructure and the form drag produced by a large-diameter engine. Increasing the turbine inlet temperature will have the opposite effect and will increase the SFC and specific thrust. These requirements are similar in the case of stationary gas turbine as increase in turbine inlet temperature and compressor pressure ratio directly impacts the cycle efficiency. The firing of the engine at an always higher temperature, however, contrasts with the requirements for component life. This aspect becomes critical since aircraft engines have to operate nowadays for 10,000 hours and up to 66,000 hours for stationary gas turbines before an inspection is planned. As a consequence, a further increase in the turbine inlet temperature becomes extremely challenging. Besides these boundary conditions, the engine efficiency can still be increased by optimizing the engine components themselves. In that regard, the secondary air system proves to be an attractive candidate. Contrary to compressor or turbine, which has already reached maturity with a polytropic efficiency of around $90\,\%$, the optimization potential of the secondary air system still has to be leveraged.

Moore (1975) also pinpointed this need for high-pressure ratio and by-pass to optimize SFC and high turbine inlet temperature for maximum thrust. The author detailed how these parameters influence the required amount of secondary air. Because of the higher pressure ratio, the internal engine pressure increases and the bearing load requirements become more difficult to meet. This would lead to an increased secondary air system demand. Furthermore, as the pressure ratio increases, the air temperature rises and its cooling potential decreases. More air would be needed then to cool down the engine components. Increasing the by-pass ratio has two main consequences for the engine. The number of low-pressure turbine components will increase, leading to a higher demand for cooling air e. g. for rim seal sealing or casing cooling. The internal engine size will be reduced and, because of downsizing, the engine will have to operate at higher speeds. It becomes then increasingly difficult to balance the loads on the bearings. The sealing gap and clearances cannot be scaled down and the sealing requirements tend to become more difficult to reach. To overcome these difficulties, more secondary air will be needed. An increased turbine inlet temperature will also have to be compensated for by more intense cooling of the first turbine nozzle guide vane (NGVs) and rotor blades. This short analysis confirms the trend for modern gas turbines to increase the required amount of secondary air. Unfortunately, increasing the bleeding air out of the primary flow has a negative impact on the SFC and specific thrust. Because of the losses in the primary mass flow, the turbine inlet temperature has to be increased to ensure an equivalent specific thrust. An increase of 11 and $7\,\mathrm{K}$ per $1\,\%$ bleed air were reported, respectively, by Moore (1975) and Alison (1991). Moore also concluded that higher by-pass and pressure ratios would worsen the impact of bleed air increasing. The removal of mass flow from the main gas path is not the only source for reduction in efficiency. The interaction between the bleed flow and the main gas path has been identified by several authors as a source of loss (Wellborn and Okiishi 1996, Shabbir et al. 1997, Wellborn and Okiishi 1999). Shabbir et al. (1997), for instance, reported a reduction of $1.5\,\%$ in pressure ratio across a high-speed transonic rotor due to a hub leakage of $0.25\,\%$ of the main gas path.

Finally, two opposite trends are revealed. On the one hand, the by-pass ratio, pressure ratio, and turbine inlet temperature have to be increased to improve the performance of the engine; on the other hand, the higher demands on secondary air with higher by-pass and pressure ratio deteriorate the thermodynamic performances.

Role and challenge in designing modern compressor bleed air system

The secondary air, as opposed to the primary air, is the air that does not flow over the aerofoil and does not directly produce work on the shaft of the gas turbine or thrust for an aero-engine. The secondary air system of a gas turbine generally consists of stationary or rotating orifices, passages, rotating ducts, sealing, and pre- and de-swirl systems (Foley 2001), creating numerous combination possibilities. The compressor bleed air system is part of the secondary air system and extracts air out of the compressor through slots or holes placed on the casings or shaft of the engine. Typical compressor bleed air setups are shown in Figure 1.1 for a CFM-56 aero-engine

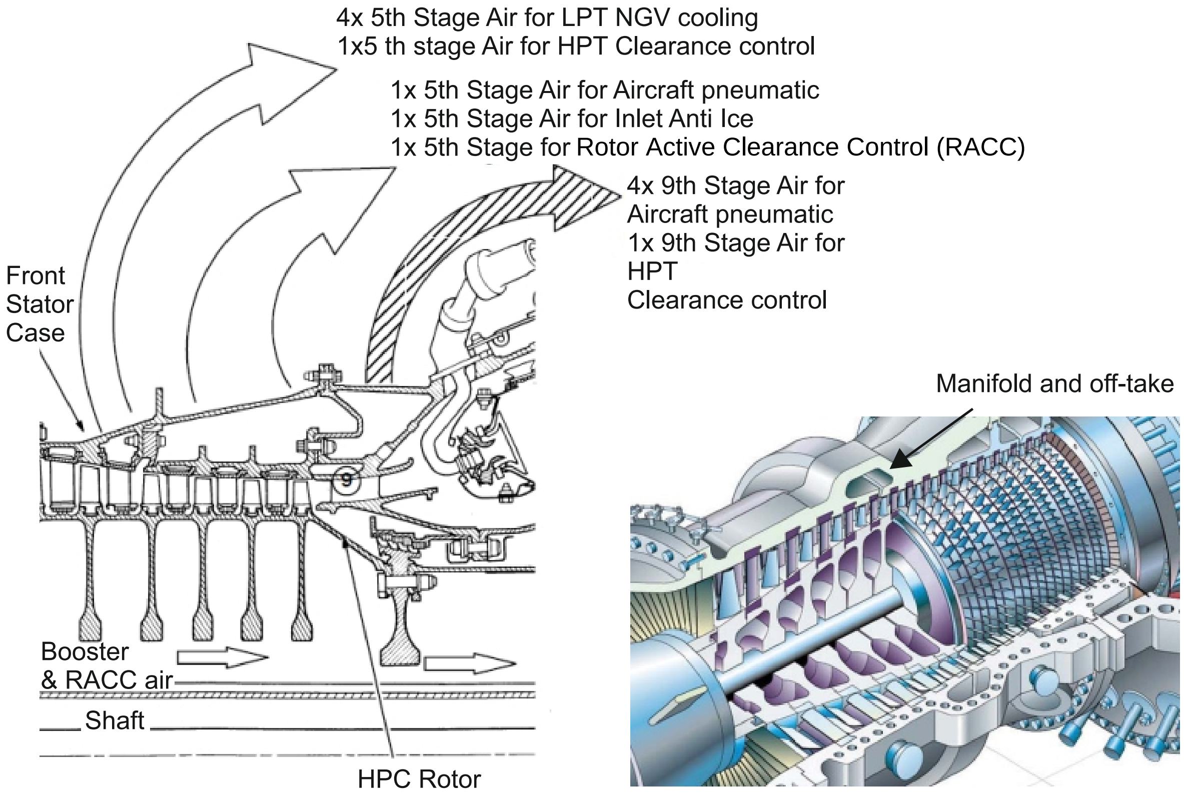

Fig. 1.1: Left: CFM56 High-pressure compressor with bleed air off-takes. Right: Manifold and off-take of an SIE 4000F (from Scholz 2018)

and a Siemens 4000F stationary gas turbine. The bleed air is collected through a circumferential manifold and is then fed into a number of exit tubes guiding the air to different applications. For instance, on the CFM-56 aero-engine, four exit tubes extract bleed air on the fifth compressor stage for the cooling of the low-pressure turbine. Some bleed valves are located along these exit tubes to control the amount of air distributed to the components. The bleed ratio is defined as the ratio of extracted mass flow to main gas path mass flow and is denoted by br in the following work. Since the bleed air does not contribute to turbine work, the bleed air extraction should be located as far upstream as possible in order to minimize its penalty on the Joule–Brayton cycle of the engine.

Secondary air systems are of prime importance for safety, reliability, and performance of an aero-engine or stationary gas turbine (Moore 1975, Foley 2001). The aim of the secondary air system is to extract up to $30\,\%$ (Foley 2001, Saravanamuttoo et al. 2009) of the primary flow through an off-take to transfer it through the engine components. This bleed air is used for:

- The cooling of engine components (rotor disk, blades) to maintain adequate steady-state and transient temperatures, increasing the expected lifetime of engine components
- The sealing of engine components to avoid leakages leading to a reduction of the primary mass flow through the aerofoil surfaces

- The sealing of cavities between disks to avoid hot gas ingestion
- The arrangement of seals to balance the engine's internal pressure to reach suitable pressure loads on the bearings
- The cooling and pressure control of the bearing system to avoid oil leakage and reduce the risk of oil fires
- In the case of the aero-engine, these internal uses are completed with customer bleeds. Through these off-takes, the compressor can supply air for cabin pressurization (a very challenging task as the cabin air is usually changed every 2 minutes), de-icing, aircraft pneumatic control, etc.

In addition to the internal and customer bleeds, handling bleeds are used to remove a portion of the compressor air during transient phases in order to maintain the compressor in its operating range (better matching of front and rear compressor velocity triangles). In cruise or at baseload, those handling bleeds are turned off but still have a critical impact on the size of the bleed. The compressor bleed air is designed for a bleed ratio of up to $30\,\%$, but most of the time extracts around 3–$10\,\%$ of the main gas path. As a result, oversized components are designed, increasing the risk of interaction with the compressor main gas path (Leishman and Cumpsty 2007, Leishman et al. 2007a, 2007b).

The location where to tap the air out of the compressor is a primary concern for engineers designing the secondary air system. The location of the bleed air should at the same time guarantee an adequate pressure level and a temperature as small as possible. Practically, the tapping location should be placed at the lowest stage possible allowing for the desired sink pressure (Moore 1975, Pfitzner and Waschka 2000, Rolls-Royce Plc 2005, Rudolph et al. 2009). The bleed air system should be optimized to reduce the pressure losses it creates as much as possible. The cooling potential of the bleed air could be optimized in that way since the lower the compressor stage, the lower the temperature of the bleed flow (Pfitzner and Waschka 2000).

Over the years, the compressor bleed air design methodology has evolved and nowadays focuses on two main criteria: minimizing the total pressure loss in the system in order to locate the off-take as far upstream as possible in the compressor and at the same time minimizing the local influence of the bleed air extraction on the compressor. Because of assembly and weight constraints, the complete compressor bleed air system must remain as compact as possible. It requires to place each component close to each other, which in turn requires to understand the interaction between each component of the compressor bleed air system: main gas path, slot (off-take), manifold, and exit tube. Additional parameters such as the structural constraints might also play an important role. Large cavities for bleeding the air out of the compressor are often paired with higher stress levels in the component, ovalization of the casing, etc. Besides those technical criteria, the financial aspect cannot be neglected and component cost is nowadays one of the major drivers for further development of gas turbine technologies. Not only will the component cost usually limit the size of the manifold to minimize the amount of raw material, it will also influence the decision to operate the manifold with one instead of several exit tubes. The cost of the casting of a stationary gas turbine casing or the cost of auxiliaries and additional piping can be reduced using fewer exit tubes. Understanding the loss in the bleed air system and its interaction with the main gas path will lead to improved design guidelines and optimized geometries capable of accommodating at best for the constraints described above.

The present work has been performed as part of the European-funded project MAin Gas Path Interaction (MAGPI) in order to judge the influence of these interactions on the two previously named design criteria. This study concentrates on investigating the flow structure changes dictated by the interaction between these components and how far they differ from the standard design tools typically used.

The present work has been divided into five chapters. First, a literature review of the relevant published works is provided in Chapter 2. Within this chapter, emphasis is given to the generated total pressure loss (see Section 2.1), depending on the component shape and location. The widely used 1D flow network solver and its assumptions and correlations are introduced in Section 2.1.1 focusing on scientific contribution including complete compressor bleed air system investigations in Section 2.1.2. Section 2.2 tackles the interaction of the bleed air with the main gas path, depending on the uniform or non-uniform characteristic of the bleed.

The test rig built at the Institute for Thermal Turbomachinery (ITS) in Karlsruhe is presented in Chapter 3 alongside its instrumentation and the post-processing applied to generate the data used in this investigation. The numerical method used to gain insight into the complex component interaction is then introduced in Chapter 4 along with its validation. The main chapter of this work, Chapter 5, introduces the results obtained in the present investigation, detailing the influence of slot, exit tube, and vanes configuration on the performance of a standard compressor bleed air system. Finally, the last chapter presents the conclusion of this investigation and some recommendations for further work.

2 Literature review

The design of an efficient compressor bleed system is challenging. The desired mass flow has to be ensured for every operating point of the engine, while the losses and effects on the core flow should be minimized. With reduced pressure losses, the air could be extracted further upstream in the compressor, limiting the negative impact of removed air on the engine thermal efficiency and improving the cooling effectiveness of the bleed air due to lower temperature. At the same time, the interaction with the main gas path must be maintained as low as possible to prevent shrinking of the compressor operating range.

In the following section, an investigation of the current state of knowledge regarding both those aspects is provided. First, the prevailing total pressure loss estimate methods are introduced. Each component of the secondary air system is individually investigated first before more specific research about the component interaction is highlighted. It is shown that the interaction between air system components is not accounted for by the current design method. Investigations including several components usually lack a detailed explanation for the origin of the component interaction.

In the second section, the interaction with the main gas path in the form of bleed non-uniformity is introduced. It is shown that the non-uniform bleeding around the compressor circumference negatively affects the compressor operating range by modifying the velocity triangle of the flow on the downstream rotor blade. A criterion for the level of non-uniformity is finally introduced and is used to investigate the component interaction influence on the non-uniformity.

2.1 Total Pressure Loss in Compressor Bleed Air Systems

2.1.1 1D-Flow Solver: Assumptions and Correlations

The overall performance of such a secondary air system is usually predicted by means of 1D and 2D correlations or numerical flow solvers (Kutz and Speer 1994, Foley 2001). These models are based on experimental results to account for the efficiency of each part of the bleed system. For instance, Zimmermann (1990) provided pressure loss coefficients for several slot geometries including the benefits of a lip design. However, the accuracy of these correlation factors suffers from the lack of experimental data. Actually, a large variety of bleed air system designs are used in industry and each of them has to work at very different operating points. The design objectives and technical solutions depend on the environment in the engine (temperature, pressure...). Furthermore, a lot of these experiments do not tackle the whole bleed air system efficiency. They focus only on a single component of the bleed air system like the off-take (Zimmermann 1990, Leishman et al. 2007b) and usually reduce the study to 2D effects. Contrary to what is modelled with these empirical parameters, the flow field in a real turbomachine is highly 3D and all the components of the bleed air system interact with each other (Gomes et al. 2006). On the other side, the experimental data can be complemented by analytical solutions resolving the complex conservation equations through an iterative solver. Again, these analytical models usually consider simplified problems (e.g., 2D and inviscid study in Dewynne et al. 1989) and are time-consuming in their creation and application.

To estimate the impact on the performance of the secondary system especially in terms of pressure losses, the conventional 1D network system is still widely used. It enable engineers to rapidly and easily calculate pressure losses, mass flows, and temperatures in a complex component network. The basics of this method were first described by Cross (1936) for water distribution networks. Some modern software, like FLOWMASTER (whose code is described in more detail in Brillert 2001), are still using the same 1D method to compute the flow distribution in a complex network such as the secondary air system. The network consists of a series of branches and nodes. The nodes are instrumenting points displaying pressure and temperature between the components. The branches are the link between the nodes and represent each component of the secondary air system (pipes and cavities constriction/expansion, seals, orifice). The mass and energy (for compressible flows) conservation equations (Eqn. 2.1) are solved at the nodes, while the momentum conservation equation is solved on the branches using a loss coefficient. The boundary conditions of the network are assumed to be known, as well as the component geometry and the relationship linking the mass flow and head loss in the component. The network solver iteratively adjusts the pressure and temperature of each node to respect the overall mass, momentum, and energy conservation in the network. For each node i among the n nodes,

$$\sum_{i=1}^{n} \dot{m}_i = 0 \tag{2.1}$$

$$\sum_{i=1}^{n} \dot{m}_i \times h_{t,i} = 0 \tag{2.2}$$

To correlate the mass flow and pressure loss, a linearized characteristic, or flow curve, is established for each component as follows:

$$\Delta p = K \dot{m}_i^2 = 0 \tag{2.3}$$

This successive substitution method does not solve the whole network in one step. The algorithm first selects a part of the network and solves the conservation equations to determine the continuity and momentum errors. The head losses and flow rates are corrected and the solver starts again on the next part of the network. When the whole network has been considered, the complete process is repeated until the continuity and momentum errors are satisfying. More modern algorithms are today available to minimize computation time and optimize convergence of the solver; for example, Majumdar et al. (1998) used a Newton–Raphson method, which has been shown to be quicker and more stable than the Cross method, while FLOWMASTER uses a Runge–Kutta fourth-order stepping process.

In addition, the swirl, which is usually dominating in turbomachines, is accounted for in a separate equation (Brillert 2001). The values of K are usually derived from theoretical considerations using empirical corrections. Kutz and Speer (1994) used such a network analysis approach to investigate the secondary air system in an aero-engine. The pressure coefficients K used are derived from simplified experiments obtained from Idelchik (1986) or Miller (1978). In his steady compressible computations, Kutz and Speer (1994) modelled a large number of components (low-pressure bearing chamber, the turbine cooling system) and obtained good agreement between experiments and simulations. Prasad et al. (2004) produced a highly detailed model of the secondary air system of an aero-engine, from the air extraction in the compressor to the mixing of secondary air with the core flow at the rear of the turbine. The authors highlighted that the accuracy of the simulations largely depends on the empirical inputs. Contrary to Kutz and Speer (1994), Prasad et al. (2004) used individual computational fluid dynamics (CFD) simulations to compute the pressure coefficients K for each component. The reasonable agreement found with the experimental results and the reduced computer costs make this technique ideal for a parameterized optimization process. Hou (2012) and Majumdar et al. (1998) pushed the model further by not only modelling steady-state compressible problems but also accounting for unsteadiness including phase changes, mixture, and external body forces, by extending the conservation equation with time-dependent variables, centrifugal forces, friction, gravity, etc. Schwarz (2005) reported experiments on a compressor bleed system composed of a $45°$ slot, a manifold, and two exit tube configurations. One of the aims of this dissertation was to assert the accuracy of the software FLOWMASTER in predicting the total pressure loss through the bleed air system. The author modelled the slot as a combination of a $45°$ flow branch, followed by a diffusor, while the manifold was modelled as an elbow part followed by a $90°$ branch. A sketch of this network is shown in Figure 5.1. After comparing the results from experiments with those of the simulation, the author reported several observations. First, the database of component geometries provided with FLOWMASTER is not sufficient to accurately model the pressure losses in every system. The author finally implemented in the software his own correlation for the slot pressure coefficient K. The second issue stems from the difficulty of the software to model the complex 3D flow patterns in the slot or in the manifold. For instance, when simulating the flow in the slot, one of the inputs for the 1D solver is the effective size of the slot. Unfortunately, due to the recirculation on the upstream side of the slot, the effective cross section of the off-take is very difficult to estimate. The author obtained satisfying results with a reduction of $50\,\%$ of the slot cross section; however, the model was not able to account for the growth in size of the recirculation zone with the bleed ratio. As a result, FLOWMASTER started underestimating the losses after $12\,\%$ bleed ratio. In the manifold with a single large exit tube at high bleed ratio, the author observed a turning back of the flow which the 1D software was not able to render. Once the secondary performance has been assessed, the secondary air system network can be inserted into larger network models like compressor or turbine in order to investigate the influence of the secondary air system on the whole engine efficiency (Torella 1991, Foley 2001).

Finally, the 1D solvers are well suited for a quick estimate of the pressure losses in a complex network of simple elements. As soon as the flow topology in the element becomes more complicated (backflow, separation), the software cannot accurately estimate the total pressure losses in the system anymore. In addition, even if the database of FLOWMASTER is already comprehensive, a huge amount of work is still required to complete it. Furthermore, this method still deals with basic components investigated in individual experiments and so without influencing each other. Creating a database where all the elements interact with each other, including small geometry details like cavity flows, bolts, etc., appears extremely challenging.

The following section provides an overview of the work done on correlations that can be applied to our specific problem for off-take, manifold, and exit tube flows.

2.1.1.1 Off-take

In the following section, a review of the losses occurring in off-takes is provided. The term off-take is used in this discussion to refer to all types of openings where bleed air is extracted. A slot is an axisymmetric type of off-take.

Influence of the off-take position
Leishman et al. (2007a) studied the effect of bleed off-take position on the static pressure drop across the off-take. In this investigation, a circular hole with a sharp leading edge is placed in a vane passage close to the vane pressure side, the suction side, or exactly at mid-pitch. The authors use a static pressure recovery coefficient between the main gas path and the plenum downstream the off-take to judge the pressure loss across the hole. Bleeding from a position near the vane pressure side provides the highest off-take static pressure recovery as it lies in the high static pressure area of the vane passage. This conclusion is valid for all bleed ratios. When the bleed ratio increases, the flow accelerates towards the off-take. The flow entering the off-take thus separates on the sharp leading edge of the off-take. In some cases, the recirculation zone covers more than $50\,\%$ of the bleeding area. This separation, whose size increases with the bleed ratio, increases the blockage in the off-take so that a reduced downstream static pressure is required for a specific bleed ratio.

Slot aerodynamics
Pressure losses in bleed air system are mostly concentrated in the slot especially for low bleed ratios (Gomes et al. 2005a). To optimize the static pressure recovery through the slot, a better understanding of the flow in the slot must be emphasized. The aerodynamic characteristics of the slot flow and the losses created by it are a complex function of both slot geometrical characteristics and flow effects, such as radius, length-to-width ratio, slot orientation to incoming flow, Mach number, and slot Reynolds number (McGreehan 1988).

To extract air out of the compressor, flow streamlines in the core flow are bent and extracted through the off-take. The abrupt change in direction (modification of the flow streamlines curvatures), contraction or expansion of the streamlines through the slot create losses and recirculation zones. The flow in vicinity of the slot is usually considered a two-regime flow (Khan et al. 1982, Thomas and Cornelius 1982, Dewynne et al. 1989): the external boundary layer flow is the flow not sucked out by the slot, while the suction slot flow is the flow entering the slot. A streamline separates those two flow regions and stagnates on the downstream corner of the slot. According to Leishman (2003), this separation line moves depending on the bleed ratio through the orifice. As the bleed ratio increases, this separation line moves further from endwall towards the free stream. Dewynne et al. (1989) performed an analytical study of a 90° slot suction in an inviscid channel for different suction rates. There is a critical suction rate where the separating streamline straightly hits the downstream slot corner between the slot and the main gas path. For a higher suction rate, the stagnation point of the reattaching streamline is located on the main gas path channel wall downstream the slot. For lower suction rates, the stagnation point is placed on the rear wall of the slot. As the suction rate decreases, the location moves deeper in the slot; however, the separation on the upstream wall of the slot prevents the stagnation point from moving further than 0.05 slot widths into the slot.