Transpiration effects in perforated plate aerodynamics

R Szwaba¹ and T Ochrymiuk¹

¹Institute of Fluid Flow Machinery Polish Academy of Sciences, Fiszera 14, 80-231 Gdansk, Poland

Abstract. Perforated walls find a wide use as a method of flow control and effusive cooling. Experimental investigations of the gas flow past perforated plate with microholes (110 µm) were carried out. The wide range of pressure at the inlet were investigated. Two distinguishable flow regimes were obtained: laminar and turbulent regime. The results are in good agreement with theory, simulations and experiments on large scale perforated plates and compressible flows in microtubules. Formulation of the transpiration law was associated with the porous plate aerodynamics properties. Using a model of transpiration flow the “aerodynamic porosity” could be determined for microholes.

1. Introduction

The motivation behind this work was to find a more efficient cooling system for the first stages of gas turbine blades. In such configurations, the coolant is supplied by the set of small holes. The film cooling process has been widely adopted on the walls of a high temperature system, such as gas turbine blades, nozzles and the walls of the combustion chamber to protect the surfaces from being overheated. Turbine airfoils of aircraft engine are small and therefore require small flow passages and film holes. For example a typical aircraft engine needs film holes diameter as small as 0.4 mm, while a typical industrial power turbine can be limited to a minimum diameter of 1 mm. The concept of microchannel cooling for gas turbine blades [14] is the natural application of thermodynamics and heat transfer to accomplish two goals: first to spread out the cooling network in a series of smaller and highly distributed channels to provide much better uniformity of cooling and thermal gradients; second to bring the cooling fluid closer to the blade surface and create more efficient heat transfer. In the past, the film jet used in the film cooling process was so big thus the amount of cooling air used was so large that it could effectively reduce the performance of a gas turbine engine. In addition, the relatively thick film jet is expected to cause rapidly mix with the hot gas in the freestream and to reduce its protection effectiveness. The challenges of microchannel cooling applications include hole plugging, wall strength, film cooling, manufacturing and costs. Up to now no commercial use of such microchannel cooling solutions was applied.

Perforated plate aerodynamics has been extensively studied over many decades by experiments [1÷7] and theory [8÷11]. The application of interest has varied: from sound absorption [12], microfilters and separators [4] and heat exchangers [13] to the method of production of a uniform turbulent flow [2] and a new concept of a blade turbine cooling technique [14]. The concept of microchannel cooling (or effusive cooling) for the gas turbine blades is a natural application of thermodynamics and heat transfer. It allows us to accomplish two goals: first to spread out the coolant to provide a much better uniformity of the cooling and thermal gradients and second to bring the cooling fluid closer to the blade surface and create a more efficient heat transfer. In the past the blade cooling process was very intensive and could reduce the performance of a gas turbine engine [15]. This paper is focused on the investigation of the aerodynamic performance of a plate with microholes using the global macroscale
experimental data. For that purpose the experiments were performed in air over a perforated plate with a perforation of 5.2% and holes 110 µm in diameter. Various ranges of pressure at the inlet were studied. This allowed us to obtain the characteristics of two distinguishable regimes: a laminar and turbulent one with the transition to turbulence at around $Re=80$. The studies were performed for various Mach numbers from $Ma<0.1$ up to the critical conditions (choking flow in the microholes). The theory of compressible gas flow in the channels has been studied by continuum and molecular approaches and can be found in various textbooks; for example, continuum [16], molecular [17] and simple analytical relations [18]. Beneath there is briefly described the basic theory required to extract the information from experimental data. The relation between the gas parameters is given as an ideal gas equation of state. Based on that equation the speed of sound $a$ can be defined as:

$$a = \sqrt{\kappa RT} = \sqrt{\frac{\kappa p}{\rho}}$$

(1)

$\kappa$ - specific heat constant, $R$ - gas constant, $T$ - temperature, $p$ - pressure, $\rho$ - density.

Another characteristic parameter of the gas relates its molecular properties to the continuum quantities. The mean free path represents an average distance between the molecules of the gas and is defined as

$$\lambda = \frac{k_\lambda \mu(T) \sqrt{2RT}}{p}$$

(2)

where $k_\lambda = \frac{\sqrt{\pi}}{2}$. The viscosity in this relation depends on the temperature and can be described as:

$$\mu(T) = \left(\frac{T}{T_{ref}}\right)^\omega$$

(3)

$\mu$ - dynamic viscosity, $k$ - thermal conductivity, $\omega$ - viscosity index, $p$ - pressure, $U$ – velocity.

The nondimensional parameters determining the relevant scales for the flow are the Mach number $Ma = \frac{U}{a}$ and the Reynolds number based on the hole’s diameter and average velocity $Re = \frac{\rho UD}{\mu}$.

2. Experimental setup

The experimental investigations were carried out in the test section shown in Fig. 1. The flow direction is from the left to the right as indicated by an arrow. The flow is a result of an imposed pressure difference between the ambient condition and pressure in the vacuum tanks, which was placed behind valve 7. The ambient condition corresponds to the air parameters at the laboratory space, e.g. temperature about 20–22 °C and atmospheric pressure. The pressure in the vacuum tanks was equal to 16 hPa. The capacity of the vacuum tanks was 120 m³, since it allows a long enough time for measurements at very low pressures where the mass flow is only about 12 standard liters per minute (SLPM). The air goes from the ambient flow through the flow meter 1, through the control valve 2 and compensatory chamber 3 to frame 4, where the membrane with microholes is mounted. Downstream of the membrane the flow goes through another chamber 5, a second valve 6 (which controls the flow condition downstream of the microholes), and the cut-off valve 7 to the vacuum tanks. The change of the stagnation parameters (pressure and density) was obtained by means of control valve 2. However, the pressure downstream of the microholes was controlled by means of valve 6. The particular characteristics can be measured throughout an adequate manipulation of these two control valves. The scheme of a measurements arrangement is shown in Fig. 2. The measurement of the stagnation parameters was located in compensatory chamber 3. The pressure was measured by means of a Prandtl probe with a Kulite pressure transducer with the full scale (FS) accuracy of 0.1%, e.g., ±1 hPa. The temperature was measured by means of the thermocouple element with an accuracy of 0.1 K.
The static pressure upstream and downstream of the membrane was measured by means of a pressure scanner with the FS accuracy of 0.05%, e.g. ±0.5 hPa. The mass flow rate was measured by means of three different laminar flow meters, depending on the range of the mass flow (Alicate: 20, 100, and 1500 SLPM; at the ambient pressure equal to 1013 hPa and the temperature of 298 K, the air density for these conditions was equal to 1.184 kg/m³). The accuracy of these flow meters was equal to ±0.01 SLPM of the measured value. The measurements were comprised of the barometric pressure; stagnation parameters upstream of the microholes, static pressure upstream and downstream of the microholes, and the mass flow rate. The pressure versus mass flow characteristics at constant pressure upstream of the measurement membrane was obtained. The following upstream microholes pressures were chosen: 25, 30, 40, 50, 100, 200, 400 and 550 hPa.

The membrane diameter was 60 mm. The membrane was produced from steel. The diameter of a single microhole was equal to 110 μm and the length was equal to 500 μm. The membrane perforation, e.g., the ratio of the surface of all holes to the whole membrane surface was equal to 5.2%, which means that the membrane contained about 15 500 microholes. A detailed view of the membrane is shown in Fig. 3. The accuracy of the estimation of the microhole diameter and length is 10 μm and 2 μm respectively.
3. Experimental results

The Reynolds number is determined by the hole’s diameter and the outlet parameters. The Mach number in the hole is a function of Reynolds numbers. As can be noted from Fig. 4, there are two distinguishable flow regimes: one for low Reynolds numbers ($Re < 10$) and one for high Reynolds numbers ($Re > 50$). The latter is related to the turbulence transition and the evidence for that is provided later. Curves in both of the regimes behave similarly and the changes are related to the adiabatic transition between the conditions of the gas. Figure 5 shows the mass flow rate as a function of the Reynolds number. The nature of the curves is not surprising since the velocity from the mass flow rate was taken into account to estimate the Reynolds number. Hence, the linear dependency between the mass flow rate $Q_h$ and the Reynolds number $Re$ is observed and plotted in Fig. 5.

![Figure 3. Schematic representation of the perforated plate ($D=110$ µm, $L=500$ µm) and the microscopic picture.](image)

![Figure 4. Nondimensional number dependencies, the Mach number as a function of the Reynolds number.](image)
In Fig. 6 the velocity in the hole is plotted as a function of the pressure difference on both sides of the perforated plate. This standard plot was first proposed by Hagen [19] and shows most clearly the transition to turbulence which occurs for cases of the inlet pressure of $P_{in}=100\div550$ hPa. The velocity of the flow should obey the following law for the laminar flow $\Delta P=P_{in}-P_{out} \sim U$ and for the transition to turbulence regime $\Delta P=P_{in}-P_{out} \sim U^{1.75}$ (see Ref. [18]). Figure 7 shows the mass flow rate changes in relation to the pressure drop. The characteristics are similar to the velocity changes and show the dependence of the velocity changes from the flow regime. Table 1 shows the best fit values for the velocity where the function is as follows:

$$\Delta P = AU^B$$  \hspace{1cm} (4)

where $A, B$ are fitting coefficients.

| $P_{in}$ [hPa] | 25 | 50 | 100 | 200 | 400 | 550 |
|---------------|----|----|-----|-----|-----|-----|
| $A$           | 0.62 | 0.04 | 0.02 | 0.02 | 0.04 |
| $B$           | 0.99 | 1.35 | 1.54 | 1.71 | 0.577 |

It can be seen that the laminar flow (Figure 6b shows an enlargement of the laminar part) has indeed, a linear velocity dependency, while the transition to the turbulence regime is different showing the similarity to the exponential function. It can be noted that the results obtained in our experiments are in agreement with the literature. The point of this work was to study microscale effects and evidence of these effects is much more difficult to find in the turbulent regime due to the insufficient theoretical description. Hence our further investigations are mainly focused on the laminar flow. Figure 7 shows the mass flow rate as a function of the pressure difference. It can be noted that the compressibility effects are large in the transitional regime. Moreover it can be seen that the transition in our experiments occurs at very similar Reynolds number as in other investigations. We obtained a transitional Reynolds number around $Re=80$ and in the case concerning the pipe of similar diameter, it has occurred for $Re=81.5$ [20].
Figure 6. Transition to turbulence, a) laminar and turbulent regime, b) only laminar regime.

In Figure 8 the universal dimensionless pressure drop results defined as $\frac{\Delta P}{\rho U_0^2}$ are plotted and can be very good illustrations of the breakdown of the laminar, friction dominated flow regime [24]. This figure shows clearly that transitional Reynolds number is around $Re = 80$.

4. Perforated plate aerodynamics

Perforated plate aerodynamics has been studied for many years, mostly focusing on plates with large holes. Both the laminar and turbulent regimes have been considered. Some specific examples can be found in the literature; for example the pressure loss coefficient over plate thickness [21], the turbulent flow over a perforated plate [2] and a very high Reynolds number ($Re > 10000$) [22]. In this section
the obtained results will be compared with the ones of two specific papers. One considers various large scale holes in different types of plates [23] and the second is a study of various shapes of microholes on a large plate [4]. The mass flow rate $Q$ is given by the equation from the empirical studies in Ref. [23]

$$Q = FS \rho h U_h$$

which by implementing the stagnation parameters transforms to:

$$Q = FS \frac{Ma_h}{1 + \frac{\kappa - 1}{2} Ma_h} \left( \frac{P_0}{RT_0} \right)^{\frac{\kappa}{\kappa - 1}}$$

$F$-perforation, $S$-perforated plate surface, $P_0=P_{in}$, h-hole.

The experimental relation derived in Ref. [23] leads to:

$$Ma_h = 1.2 \left( \frac{\Delta P}{P_0} \right)^{0.55}$$

Curve representing the equation (7) (B/D model) is plotted in Fig. 9 together with experimental data. Two regimes are clearly seen. The turbulent flow for the highest inlet pressures fits well to the relation derived from the experiments in Ref. [23]. The laminar flow and turbulent one at low Reynolds number behave differently. The exact fitting coefficients are presented in Table 2, where the function is given by the equation:

$$Ma_h = A \left( \frac{\Delta P}{P_0} \right)^{\eta}$$
Figure. 8. Illustration of the breakdown of laminar friction dominated flow.

Table 2. Coefficients for the Mach number pressure drop dependency (see Eq. (8))

| $P_{in}$ [hPa] | $A$  | $B$  |
|---------------|------|------|
| 30            | 0.18 | 1.01 |
| 40            | 0.25 | 0.96 |
| 50            | 0.32 | 0.93 |
| 100           | 1.16 | 0.65 |
| 200           | 1.3  | 0.53 |
| 400           | 1.43 | 0.5  |
| 550           | 1.95 | 0.49 |

It can be seen that the coefficient $B$ for the laminar flow is twice as large as the one for the transition to turbulence. This means that at lower Reynolds numbers, for the same pressure drop, there is an
increase in the importance of viscous effects. The results confirm that despite the small size of the holes in our experiments the global plate aerodynamics fits very well to the large scale investigation. However to extend B/D model it need to be introduced variables as function of $P_{\infty}$ coefficient $A=A(P_{\infty})$ and $B=B(P_{\infty})$ in equation (8). These functions are a polynomials of the 4$^{th}$ order and probably they fit well only for our specific experiments. Therefore the B/D model needs further development and modification by using some detailed insightful theoretical aerodynamical models.

![Graph](image)

**Figure 9.** Comparison with the other experiments for the perforated plates, B/D model for perforated plates in parallel flow.

5. Conclusions
This paper focuses on the experimental investigation of the perforated plate aerodynamics for wide ranges of Reynolds numbers. It was shown that two Reynolds dependent regimes existed: the laminar one and the transition to turbulence occurring at $Re=80$. The observed Reynolds number value for the transition to turbulence is very low. It confirms observations performed by other researchers, where transition to turbulence in microchannel is present for Reynolds numbers much smaller than in the macroscale. The carried out experiment is the first one which shows the turbulent transition on the perforated plate with microscale influence. The perforated plate had the holes of a micrometre size (110 µm). The experimental results were compared with compressible experimental models for a large scale [23]. For all of these cases, the measured values agreed only for high Reynolds numbers regions. To confirm that a more extensive study with various plate perforation models and flow parameters would need to be performed.

It was observed during the experiments that small increase of mass flow through the perforated plate was accompanied by high pressure losses what can be an important parameter in potential application of effusive cooling technique in gas turbines. Therefore the future work should be also focused on finding the optimal coolant mass flow, adequate for blade thermal loading and simultaneously not introducing to much pressures drop and losses in turbine blades cooling system.

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