International Journal of Heat and Mass Transfer 127 (2018) 727–742

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Low order modeling method for assessing the temperature of multi-perforated plates

Romain Bizzari [a,*], Dorian Lahbib [a,b], Antoine Dauptain [a], Florent Duchaine [a], Stephane Richard [b], Franck Nicoud [c]

[a] CERFACS - 42, Av. Gaspard Coriolis, 31057 Toulouse cedex 1, France
[b] Safran Helicopter Engines - Avenue Joseph Szydlowski, 64510 Bordes, France
[c] IMAG, Univ. Montpellier, CNRS, Montpellier, France

ARTICLE INFO

Article history:
Received 21 January 2018
Received in revised form 1 June 2018
Accepted 10 July 2018

Keywords:
Effusion cooling
Conjugate heat transfer
Large-Eddy simulations
Adiabatic computations
Coupled computation
Modeling

ABSTRACT

A low-order model is proposed to predict the temperature of a multi-perforated plate from an unresolved adiabatic computation. Its development relies on the analysis of both an adiabatic and a conjugate heat transfer wall resolved large eddy simulation of an academic multi-perforated liner representative of the cooling systems used in combustion chambers of actual aero-engines. These two simulations show that the time averaged velocity field is marginally modified by the coupling with the heat diffusion in the perforated plate when compared to the adiabatic case. This gives rise to a methodology to assess the wall temperature from an unresolved adiabatic computation. It relies on heat transfer coefficients from referenced correlations as well as a mixing temperature relevant to the flow in the injection region where the cold micro-jets mix with the hot outer flow. In this approach, a coarse mesh simulation using an homogeneous adiabatic model for the aerodynamics of the flow with effusion is post-processed to provide a low cost alternative to conjugate heat transfer computations based on hole resolved meshes. The model is validated on an academic test case and successfully applied to a real industrial combustion chamber.

1. Introduction

To improve gas turbines efficiency, aeronautical engines manufacturers increase both the compressor pressure ratio and the turbine inlet temperature. A direct consequence is the increase of the thermal constraints imposed to the walls of the combustion chamber. Since the typical materials used in combustors cannot sustain more than 1100–1200 K before melting, controlling the temperature of the solid boundaries without compromising the overall efficiency of the engine is a critical issue. In modern combustors, effusion cooling [41] is often used to control the temperature of the walls surrounding the flame tube (see Fig. 1).

The casing being at a higher pressure than the flame tube, a micro-jet is formed at each aperture of the multi-perforated plate. The coalescence of these micro-jets induces a film region where the hot gases from the combustion chamber side mix with the fresh air from the casing. A sketch which displays the principle of effusion and important parameters is given in Fig. 2.

The general problem in cooling systems is to predict, for a given geometry and operating point, the coolant mass flow rate necessary to maintain the temperature of the plate below a critical value. The efficiency of this system is driven by many parameters (jet-to-jet distance, perforation arrangement, hole shape, size and inclination). In order to quantify the effect of these parameters, many arrangements have been studied in the literature. It has been shown that staggered inclined perforations offer a better protection than in line inclined perforations [51,40,18,31]. Also the optimal lateral (Δx) and spanwise (Δz) hole distances have been found [46,65,59] in the range $4d - 8d$, where d is the hole diameter. From the distances between holes ($\Delta x, \Delta z$) and the diameter of the aperture (d) reported in Fig. 3, the plate porosity σ can be computed. It represents the ratio between the perforated surface and the total surface of the plate:

$$\sigma = \frac{\pi d^2}{4 sin(\alpha)} \frac{1}{\Delta x \Delta z}, \quad (1)$$

where α shown in Figs. 2 and 3, is the angle between the streamwise and the perforation directions.

* Corresponding author.
E-mail address: bizzari@cerfacs.fr (R. Bizzari).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.059
0017-9310/

Nomenclature

Δx	streamwise pitch [m]
Δz	spanwise pitch [m]
C_P	specific heat capacity of the plate [J/K/kg]
d	diameter of the aperture [m]
D_R	density ratio [–]
J	momentum ratio [–]
L	perforation length [m]
M	blowing ratio [–]
Nu	Nusselt number [–]
Pr	Prandlt number [–]
q	heat flux [W m^{-2}]
Re	Reynolds number [–]
S_t	Stanton number [–]
T	temperature [K]
Greeks	
α	injection angle [°]
η	effectiveness [–]
η_{ad}	adiabatic effectiveness [–]
λ	thermal conductivity [W m^{-1} K^{-1}]
Φ	global heat flux [W m^{-2}]
ρ	density [kg m^{-3}]
σ	porosity [–]
Θ	non dimensional temperature divided by the adiabatic temperature [–]
θ	non dimensional temperature [–]
Acronyms	
CFD	Computational Fluid Dynamics
CHT	Conjugate Heat Transfer
CPU	Central Processor Unit
LES	Large Eddy Simulation
RANS	Reynolds Averaged Navier Stokes

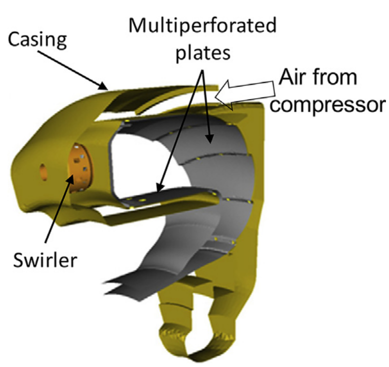

Fig. 1. Sector of an annular helicopter combustion chamber taking into account the swirler, the flame tube and the chamber casing. Extracted from [28].

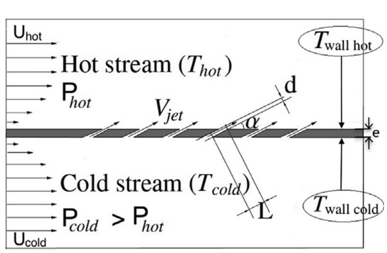

Fig. 2. Schematic view of a multi-perforated plate which separates the combustion chamber (hot gases) from the casing (cold gases) presented on Fig. 1.

As for the classical jet-in-cross flow configurations [61], the flow regime around a multi-perforated plate is piloted by the blowing (M) and the momentum (J) ratios defined as:

$$M = \frac{\rho_{jet} V_{jet}}{\rho_{hot} U_{hot}}, \tag{2}$$

$$J = \frac{\rho_{jet} V_{jet}^2}{\rho_{hot} U_{hot}^2}, \tag{3}$$

where ρ_{jet} and V_{jet} denote the jet density and the jet velocity respectively while ρ_{hot} is the density of the hot gases in the combustion chamber and U_{hot} is the streamwise velocity of the hot gases (see Fig. 2).

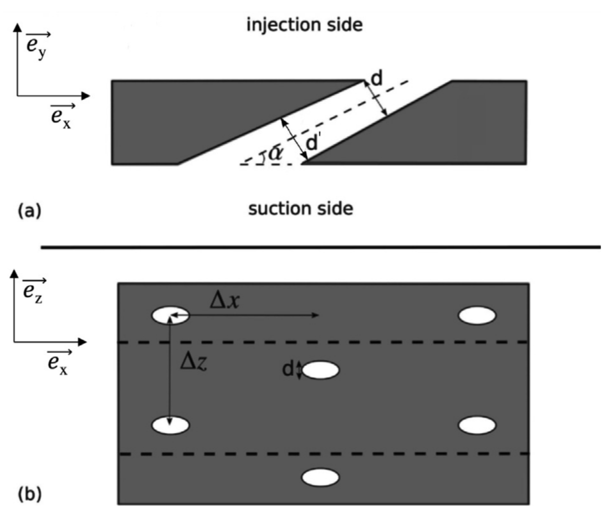

Fig. 3. (a) Detailed side view of the perforation, (b) top view of the plate with the periodic domain calculated (dotted).

Ammari et al. [1] underlined that M and J also impact the heat fluxes through the density ratio D_R defined as:

$$D_R = M^2/J = \frac{\rho_{jet}}{\rho_{hot}}. \tag{4}$$

Gustafsson [30] showed that the Mach number does not play a significant role on the cooling effectiveness at least in the flow regimes characteristic of typical industrial applications. Eriksen and Goldstein [22] and Champion [13] drew the same conclusion for the Reynolds number of the injection flow. Therefore, when comparing the efficiency of multi-perforated cooling systems, the operating point is suitably defined once M and J have been selected.

The cooling effectiveness η is a non-dimensional quantity usually introduced to characterize the thermal efficiency of effusion [45]; it is defined as:

$$\eta = \frac{T_{hot} - T_{wallhot}}{T_{hot} - T_{cold}}, \tag{5}$$