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# Experimental and numerical investigation on the role of holes arrangement on the heat transfer in impingement/effusion cooling schemes

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In the present work, two different impingement/effusion geometries have been investigated, both having staggered hole configuration and an equal number of impingement and effusion holes. The first geometry, which is designed in case of low coolant availability, has impingement hole pitch-to-diameter ratios of 10.5 in both orthogonal directions, a jet-to-target plate spacing of 6.5 hole diameters, with effusion holes inclined of 20° with respect to the target surface. The second geometry, which is designed in case of high coolant availability, has impingement hole pitch-to-diameter ratios of 3.0, a jet-to-target plate spacing of 2.5 diameters and normal effusion holes. For each geometry, two relative arrangements between the impingement and effusion holes have been investigated, as well as various Reynolds numbers for the sparser geometry. The experimental investigation has been performed by applying a transient technique, using narrow band thermochromic liquid crystals (TLCs) for surface temperature measurement. A CFD analysis has also been performed in order to support interpretation of the results. Results show unique heat transfer patterns for every investigated geometry. Weak jet-jet interactions have been recorded for the sparser array geometry, while intense secondary peaks and a complex heat transfer pattern are observed for the denser one, which is also strongly influenced by the presence and position of effusion holes. For both the geometries, effusion holes increase heat transfer with respect to impingement-only, which can be mainly attributed to a reduction in flow recirculation for the sparser geometry and to the suppression of spent coolant flow for the denser one.

## 1. Introduction

Gas turbine development is characterized by a continuously increasing turbine inlet temperature, which is beneficial for the efficiency and power output of the engine. The main drawback of this trend is the corresponding enhancement of thermal loads on all engine components exposed to the hot gas flow. To sort out this issue, cooling systems have been developed to keep material temperatures to a level that ensures an adequate lifespan of hardware. In modern gas turbines, different cooling techniques are usually applied simultaneously: the interaction among the various systems can strongly affect the performances of the single system. Accordingly, a study of the complete cooling configuration is often required to determine its performance: some interesting applications can be found in previous studies carried out by the authors [1–3].

A highly effective cooling system, widely used in combustor liners and nozzle guide vanes, is the combination of impingement and effusion cooling. In this configuration an array of impinging jets is generated by a perforated baffle which cools down the wall opposite to the hot gas path. The spent coolant then feeds an array of effusion holes through the target wall itself and is evacuated on the hot side, creating a protective film layer. The area averaged heat transfer coefficient (HTC) on the cold side of the target wall can be up to 55% higher than the ones obtained with impingement alone [4], and up to 10 times the values of effusion only [5]. Heat transfer enhancement by impingement alone is dependent upon the suppression of spent coolant flow (crossflow), which deflects coolant jets and degrades impingement performance [4,6,7]. The interaction between impingement and effusion flow fields can increase heat transfer even without crossflow, mainly thanks to the reduction of flow re-entrainment [8,9], while a minor role seems to be played by flow acceleration near the effusion holes [8,10]. The presence of impingement plate itself can also be beneficial for hot gas side protection [11]. The overall pressure drop

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**Nomenclature**

*Acronyms*

| | |
|---|---|
| *CFD* | Computational Fluid Dynamics |
| *HTC* | Heat Transfer Coefficient |
| *RANS* | Reynolds-Averaged Navier-Stokes |
| *SAS* | Scale Adaptive Simulation |
| *TLC* | Thermochromic Liquid Crystals |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity [$m^2/s$] |
| $\beta$ | angle respect to plate [deg] |
| $\mu$ | dynamic viscosity [Pa/s] |

*Latin symbols*

| | |
|---|---|
| $\dot{m}$ | mass flow rate [kg/s] |
| $A$ | area [$m^2$] |
| $D$ | diameter [m] |
| $G$ | mass flow rate over area ratio [$kg/m^2$ s] |
| $h$ | convective heat transfer coefficient [$W/m^2$ K] |
| $k$ | thermal conductivity [W/mK] |
| $N$ | number of holes [–] |
| $Nu$ | Nusselt number [–] |
| $Re$ | Reynolds number [–] |
| $S$ | thickness [m] |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $x$ | streamwise direction [m] |
| $X$ | jet-to-jet spacing ($x$ direction) [m] |
| $y$ | lateral direction [m] |
| $Y$ | jet-to-jet spacing ($y$ direction) [m] |
| $Z$ | jet-to-target plate spacing [m] |

*Subscripts*

| | |
|---|---|
| 0 | Geometry 2 (impingement only), first row |
| *e* | effusion |
| *i* | impingement |
| *init* | initial |
| *j* | impingement jet |
| *w* | wall |

across the liner is indeed distributed between the two layers with the impingement perforations usually set as metering orifices for prescribing the mass flow. This allows to maintain high effusion holes apertures with a reduced pressure drop thus decreasing the jet penetration and improving film cooling development [12].

According to previous discussion, it is evident that impingement/effusion cooling schemes represent a feasible strategy to increase cooling efficiency and save coolant. However, the implementation of such systems needs to be evaluated taking into account some possible detrimental aspects. First of all, cost and weight of double wall impingement/effusion scheme are generally higher than simple effusion systems. Moreover, a combination of parameters which maximizes cold side heat transfer may not correspond to an optimal condition in terms of hot side film effectiveness: the ensemble of all the design parameters needs to be considered in order to retrieve the best performance in terms of liner thermal stresses reduction [13]. As a consequence, each particular system requires a dedicated analysis to be performed.

The present work focuses on the measurement of HTC distribution on the cold side of the effusion plate of two distinct impingement/effusion systems with different geometric parameters. The effects of the relative positioning of impingement and effusion arrays, as well as of the impingement jets Reynolds number, are experimentally investigated. The analysis of the heat transfer distribution on the inner side of the effusion plate is supported by CFD simulations: the combination of measured and calculated data enables a complete analysis of thermal and fluid-dynamic phenomena, and thus provides significant information on the unique behaviour of each geometry. A similar approach have been already followed by the authors in the past for the investigation of different cooling configurations based on impinging jets [14–16].

## 2. Experimental investigation

### 2.1. Test rig and measurement techniques

Measurements were performed in the Heat Transfer and Combustion Laboratory of the Department of Industrial Engineering of the University of Florence (DIEF).

The test rig (depicted in Fig. 1) consists of an open-loop, suction type wind tunnel, and is designed to replicate, on an enlarged scale, the thermal and fluid-dynamic phenomena of a combined impingement/effusion cooling system. The vacuum system is composed by four inverter controlled vacuum pumps, with a total maximum capacity of about 2400 $m^3/h$, which pull air at ambient pressure and temperature into the rig inlet section. Since a transient technique is used for heat transfer measurements, air needs to undergo a fast and uniform temperature change. As a consequence, the first component encountered by the air flow is an ad hoc prepared six stage mesh heater. The number of active stages is defined by the required thermal power. Electric power is provided to the stages by dedicated DC power supplies. A straight PMMA duct connects the mesh heater to the cooling geometry model. The small length (200 mm) and the low thermal conductivity of the material (0.19 W/mK) allow to preserve the uniform temperature profile of the heated air flow.

The cooling geometry is entirely made of transparent PMMA to provide both thermal insulation and optical access to the inner surfaces. The impingement/effusion system is replicated by two parallel plates, housing the impingement (I) and effusion (E) holes arrays, and a spacer, built as a square frame, which separates the two plates and defines the impingement-to-target plate spacing.

Two main configurations have been investigated, which will be referred to as Geometry 1 and 2. The corresponding impingement and effusion plates will be indicated as I1 and E1 for the first Geometry, and I2 and E2 for the second one. A scheme of such geometries is reported in Fig. 2. Each configuration presents an equal number of impingement and effusion holes, arranged in staggered arrays. Geometric features of the two geometries are summarized in Table 1, namely impingement jet-to-jet spacings in both orthogonal directions $x$ and $y$ defined on the plate itself ($X$ and $Y$), jet-to-target plate spacing ($Z$), effusion hole diameter ($D_e$), impingement and effusion plates thickness ($S_i$ and $S_e$). All values are scaled with respect to the impingement hole diameter ($D_i$). The inclination of holes axes with respect to the plate surface ($\beta_i$ and $\beta_e$) is also reported, as well as the number of impingement and effusion holes $N_i$ and $N_e$.

Differences in geometric features of the two schemes reflect their design targets. The two geometries share the same values of impingement and effusion plate thickness, as well as the same gap between them. Geometry 1 is designed in case of low coolant availability, thus presenting smaller holes and features aimed at