Impingement cooling advances to improve gas turbine efficiency

DNS study of the turbulent inflow effects on the heat transfer from a heated flat surface to a circular impinging jet

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In Short

- Understating the impingement jet cooling is relevant for the improvement of gas turbine performances.
- Vortex dynamics governs the heat transfer to impinging jets and is not fully understood yet, because the underlying physical phenomena occur at very small time and length scales.
- DNS only will enable us to gain more insights, because such small scale phenomena are hardly captured by experiments and not at all by LES or RANS computations.

Because of the growing worldwide contribution of renewable energy to electricity supply, the shares of fluctuating sources in the mix have in recent decades sensibly increased. As a consequence, gas turbine power plants have assumed a crucial role in providing stability to the electrical networks by ensuring the instantaneous supply-demand balance. Efficient gas turbines are also demanded in the aviation, which still constitutes an irreplaceable means of transport for journeys over 1000 km. In recent decades, thanks to the progress in the thermo-fluid dynamic performances of turbomachinery, the efficiency of gas turbines has considerably increased. For instance, the overall efficiency of today's gas turbine power plants is approximatively 40%: twice that of their early ancestors. In order to save fuel and reduce greenhouse gas emissions, further efficiency improvements are highly desirable. Nonetheless, additional significant advances in the design of the mechanical components are challenging to achieve and would improve only marginally the overall efficiency of the system, because their efficiency has already reached by now values above 90%. The major energy conversion losses are indeed attributable to the thermodynamic cycle, namely the Brayton cycle, whose design has remained nearly unchanged for more than hundred years.

For this reason, the purpose of the Collaborative Research Center (CRC) 1029 is to increase the efficiency of gas turbines by more than 10% through the use of unsteady combustion and flow dynamics. Notably, a pulsed detonation approach is investigated in order to achieve a quasi-constant-volume combustion. The adoption of an unsteady combustion concept, however, will deeply affect not just the combustor, but also the functionality of all the components of the turbine, which should be redesigned so that they can resist stronger thermal and mechanical stresses.

In this context, impinging jets are particularly relevant because they are used to cool down the most thermally stressed components of the turbine, namely the first stages of the expander. The implementation of a pulsating, non-stationary combustion will require the development of new impinging jet cooling techniques, in order to cope with possible hot-gas injections into the core of the machine.

Moreover, the use of impinging jets is not limited to gas turbine applications. They are successfully employed as high-performance heat transfer mechanisms in a considerable number of other industrial and engineering configurations, such as in electronics, drying of textiles and paper etc. Recent studies have focused on developing techniques aimed at enhancing the efficiency of impingement cooling devices by using non-stationary configurations. For instance, it has been shown that an impinging jet with pulsating inlet provides substantially higher heat transfer than a non-pulsating one [1].

In general, impinging jets are able to provide a high heat flux not just near the stagnation point, but also at higher distances from the jet axis r/D, where D is the jet diameter. The extra heat transfer originates from a vortex system impinging on the plate (primary vortices), which couples with secondary vortices generated close to the impingement plate and forms bunches of vortices travelling over the impingement plate in radial direction (vortex rings) [2]. In the region where the vortex rings generate, very high temperature gradients are observed, which lead to a secondary maximum of the heat flux at r/D between 1 and 2. Depending on the Reynolds number Re (based on the jet diameter and velocity), the second peak turns first into an inflection point, until it disappears, as the distance between the jet exit and the impingement plate H/D becomes larger [3].

Despite the strong research effort, it has not been made clear yet what is the effect of the flow regime (laminar or turbulent) of the jet at its exit on the heat transfer at the plate. This is particularly relevant because in real applications the inflow will be likely turbulent. By performing direct numerical simulations (DNS) with $H/D = 5$ and $Re \simeq 8000$, we observed that a turbulent inflow hinders the formation of the primary vortices (Fig. 1) and thus the occurrence of secondary peak (or inflection point). This can be seen by looking at Fig. 2, which compares the mean heat flux profile in the laminar and turbulent inlet cases in terms of mean Nusselt number,

$$\overline{Nu} = \frac{hD}{\lambda},$$

where h is the convective heat transfer coefficient of the flow and k is the thermal conductivity of the fluid.

Dairay et al. [4] showed that at a similar $Re = 10,000$ but lower $H/D = 2$, a secondary peak is observable even when turbulent inflow conditions are used[1]. Given the absence of the primary vorticity, this brings us to the conclusion that the phenomena leading to the formation of the secondary maximum change when the jet issues in fully turbulent conditions.

In order to understand the different causes of the secondary peak, we aim at performing a DNS at $Re = 8000$ and $H/D = 2$ with a fully developed turbulent inlet issuing from a long pipe. This will be achieved by coupling the impinging jet simulation with an injection pipe of length $3D$. The inflow of the pipe will be enforced by copying time-dependent density and velocity profiles from an auxiliary fully developed turbulent pipe flow simulation performed with a pipe $18D$ long. The temperature of the hot plate will be 80 K higher than the total temperature of the cold jet at its exit.

DNS data will provide insights on the phenomena responsible for the heat and mass transfer near the plate, which are often not detectable in experiments or are not at all resolved in RANS or LES computations, because of the very small time and length scales they occur at.

[1] Dairay et al. [4] focused their analysis on the case with a turbulent inflow issuing from a short converging nozzle, which is known to lead to a non-developed profile, sensibly different than the profile that occurs at the exit of a long pipe, here addressed.

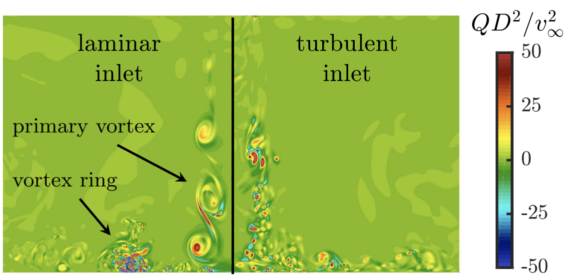

Figure 1: *Radial sections of the laminar inlet and turbulent inlet impinging jets coloured by the second invariant of the velocity gradient tensor Q normalized with the reference velocity v_∞ and jet diameter D. High values of Q identifies vortices. (Turbulent inlet data after Ref. 2.)*

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More Information

[1] T. Janetzke. *Experimentelle Untersuchungen zur Effizienzsteigerung von Prallkühlkonfigurationen durch dynamische Ringwirbel hoher Amplitude*. PhD thesis, TU Berlin, 2010.

[2] R. Wilke and J. Sesterhenn. Statistics of fully turbulent impinging jets. *Journal of Fluid Mechanics*, 825:795–824, 2017. doi: 10.1017/jfm.2017.414

[3] R. Viskanta. Heat transfer to impinging isothermal gas and flame jets. *Experimental thermal and fluid science*, 6(2):111–134, 1993. doi: 10.1016/0894-1777(93)90022-B

[4] T. Dairay, V. Fortuné, E. Lamballais, and L.-E. Brizzi. Direct numerical simulation of a turbulent jet impinging on a heated wall. *Journal of Fluid Mechanics*, 764:362–394, 2015. doi: 10.1017/jfm.2014.715

Project Partners

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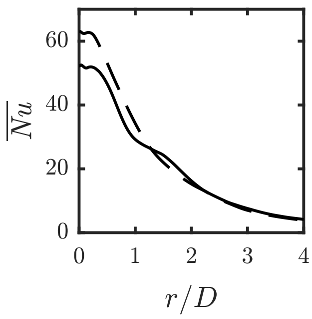

Figure 2: *Mean Nusselt number $\overline{Nu}$ on the impingement plate for the simulation at $Re \simeq 8000$ and $H/D = 5$: solid line, laminar inlet; dashed line, turbulent inlet. (Turbulent inlet data after Ref. 2.)*