Industrial Scale Test Rig for Flow and Heat Transfer Characterisation of Impingement Jets

J. E. Menzler | E. Trampe | N. Rademacher | J.-H. Rieger | H. Pfeifer | C. Wuppermann

Impingement Jet Heat Transfer

Nozzle systems are utilized in metal production for the heat treatment of steel, aluminium and copper strip to heat and cool the material in continuous processing lines and in chamber furnaces. Further applications are production and finishing of flat glass and drying of paper or textile tapes. The nozzles are directed onto the strip in such a way that the resulting impingement gas flow ensures a high and homogeneous heat or mass transfer. In addition, the resulting pressure pad on the surface can be used to float the strip contact-free through the plant.

Figure 1 shows the schematic velocity field of an impingement flow of two nozzles with its relevant geometric dimensions. The flow exits a round or slot nozzle and initially spreads out in the ambient like a free jet. A stagnation zone is built up near the wall. Here, the jet is decelerated and deflected parallel to the surface. Downstream of the deflection, the jet spreads out in a wall boundary layer and eventually mixes with another wall jet in a back flow region.

Heat is transferred between the flow and the surface by forced convection and is affected by the thermophysical properties of the gas (resp. Prandtl number *Pr*), the nozzle exit velocity (resp. Reynolds number *Re*), as well as the arrangement of the nozzle array (nozzle distance *s*, strip distance *H*) and the nozzle geometry itself (hydraulic outlet diameter D_H, nozzle shape). The heat transfer is characterised by the heat transfer coefficient *h* which is defined by the ratio of local heat flux density *q* and the temperature difference between the surface (T_s) and nozzle exit (T_e).

$$h := \frac{q_{conv,forced}}{T_s - T_e} = f\left(Re\,,Pr\,,\frac{H}{D_H}\,,\frac{s}{D_H}\,,\ldots\right) \quad , \quad Re = \frac{\rho v_e D_H}{\mu}$$

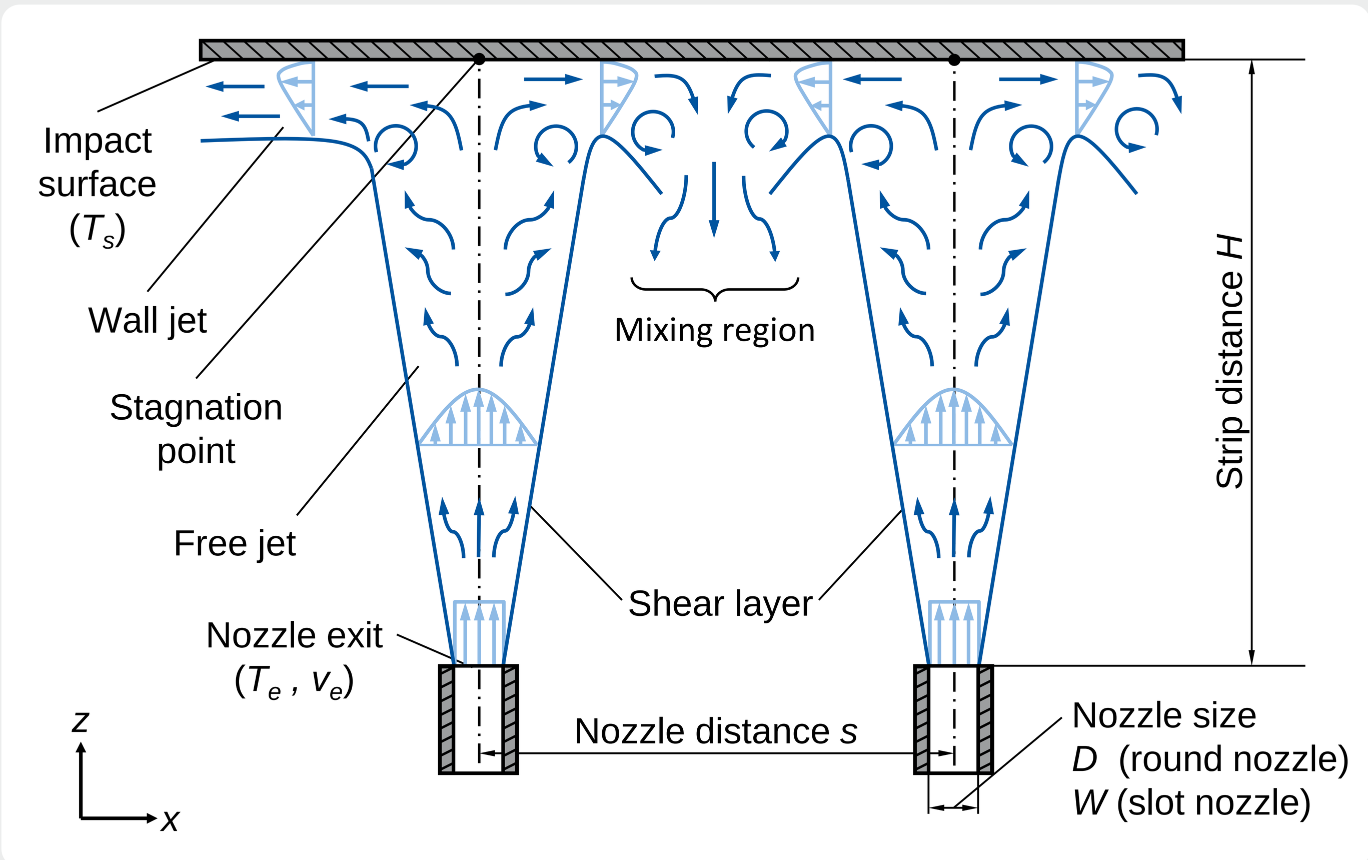

Figure 1. Flow field of an impinging jet

Measurement Method

Since the flow characteristics of impingement jets has direct effect on its heat transfer properties, the aim of the experimental setup is the simultaneous investigation of both the convective heat transfer and the flow field.

Heat Transfer

The impingement surface is represented by a thin *Constantan®* strip that can be heated by direct electrical resistance heating. The impingement flow, which emerges from the nozzles at ambient temperature, causes a local temperature distribution on the surface due to convective heat transfer. The strip is considered thermally thin with the resulting Biot numbers (*Bi* = 0.0001 … 0.001). It can therefore be assumed for the measurement that the temperature on the impact surface is the same as on the side facing away from the flow. On this side, the temperature is measured using infrared thermography, with each pixel of the IR camera corresponding to a section of around 1 mm² on the surface with a certain temperature. In a steady state, the local heat transfer coefficient can be determined from an energy balance around each of these 1 mm x 1 mm cells. The heat flow rates taken into account are shown in Figure 2.

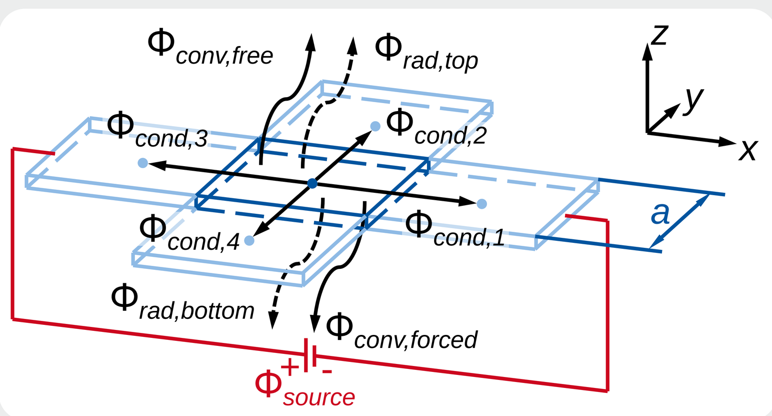

Figure 2. Energy balance and heat fluxes

Flow

Essential flow variables are measured directly and can be analysed online. The static pressure and temperature in the distribution box are determined. In addition, the volume flow in the intake section is derived by a net measurement of the dynamic pressure.

The velocity field and other flow parameters that can be derived from it (e.g. turbulence intensity) are determined using particle image velocimetry (PIV). For this purpose, a laser plane is placed through the nozzle field and particles are added to the flow which reflect the laser radiation. Two images of the flow are taken in quick succession using a special PIV camera. A 2D velocity distribution of the flow can be determined by computerised analysis of the particle movement in the images. By using additional cameras, the third velocity component can also be measured using so-called stereo PIV.

The test rig is enclosed in wooden panels to protect the surroundings and the operator from laser radiation. Laser protection curtains are fitted in places that require better accessibility.

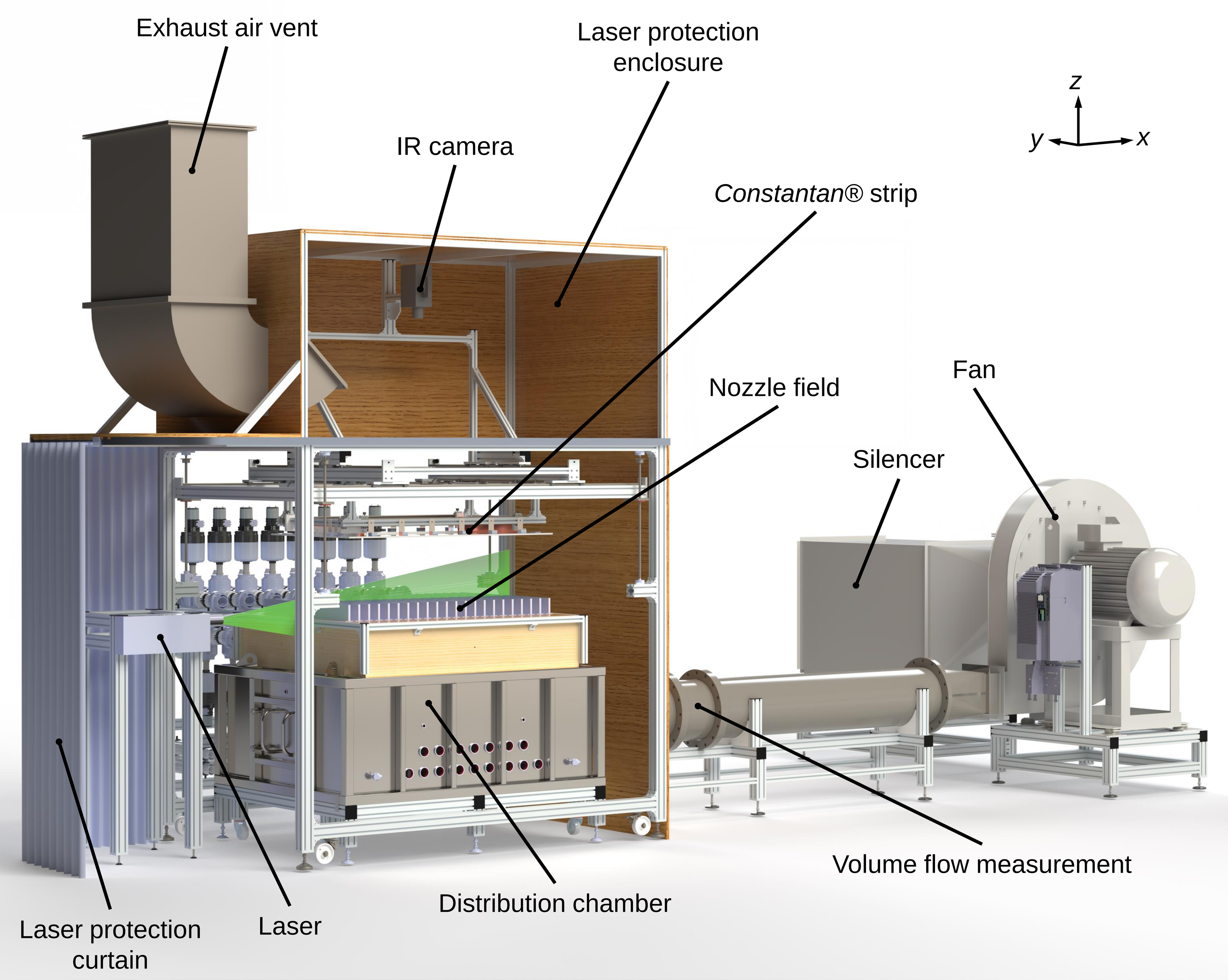

Figure 3. Test rig, dimensions: 8 m x 5 m x 4 m

Technical Specifications

In addition to the sensors, the test setup consists of a fan, a volume flow measuring section, a distribution chamber, an exchangeable nozzle field and an the electrically heated *Constantan®* strip. The main specifications of the test rig are described below.

- Radial fan
  Drive power: 90 kW_{el}
  Rotational speed: 3000 rpm
  Pressure Increase: 22,800 Pa
  Volume flow rate: 10,800 m³/h
- Nozzle field
  Max. exit velocity: 190 m/s
  Dimensions: 1480 mm × 1560 mm
  Strip distance: 0 … 250 mm
- *Constantan®* strip
  Surface Area: 1160 mm × 630 mm
  Strip Thickness: 100 µm
  Heating power: 37.8 kVA
- IR camera
  Resolution: 640 × 480 px (~ 0.3 MP)
- PIV camera
  Resolution: 5312 × 3024 px (~ 16 MP)
  Shutter time: 0.5 ms
- Nd:YAG laser
  Wavelength: 532 nm (green light)
  Pulse energy: 200 mJ
  Pulse length: 6 … 9 ns

Results

The investigation of the heat transfer is primarily based on the surface temperature measurement by the IR camera. Figure 4 shows the exemplary temperature distribution on the strip surface above an array of five straight slot nozzles. The temperature is lowest near the stagnation point and highest in the back flow region. The artefact with increased temperature, across the image in the *x*-direction at a depth of *y* ≈ 0 mm, is caused by fluid mechanical effects caused by spacers within the nozzles and is a good example show that the flow has a direct influence on the heat transfer.

The corresponding distribution of the local heat transfer coefficient of the slot nozzle field is shown in Figure 5. The heat transfer is at a maximum at the colder spots and therefore results in a high heat transfer coefficient.

The impingement flow is also investigated directly in order to analyse the influences on the heat transfer in detail. Snapshots of the velocity field can be taken using PIV. The data from these snapshots are then averaged over a sufficiently long period of time to analyse the quasi-steady velocity field.

Figure 6 shows a snapshot of a single impingement jet from a slot nozzle with a strip distance of *H* = 40 mm. It can be seen how the free jet exits the nozzle at *z* = 0 mm. As the distance to the nozzle increases, the jet widens slightly and begins to decay due to an exchange of momentum with the stationary environment. The velocity decreases further near the stagnation point and is deflected parallel to the wall, whereby individual vortices detach from the wall. These vortices can lead to secondary maxima of heat transfer at certain strip distances.

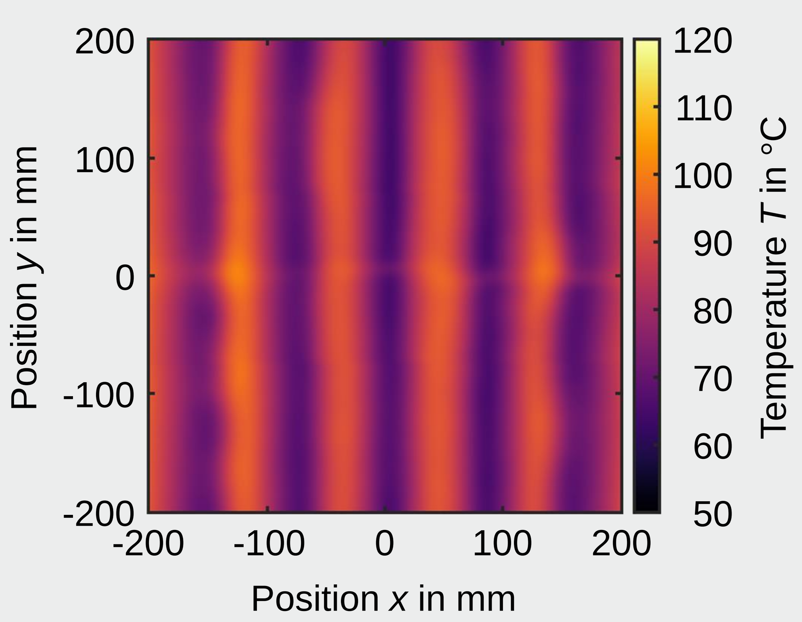

Figure 4: Infrared image of the *Constantan®* strip

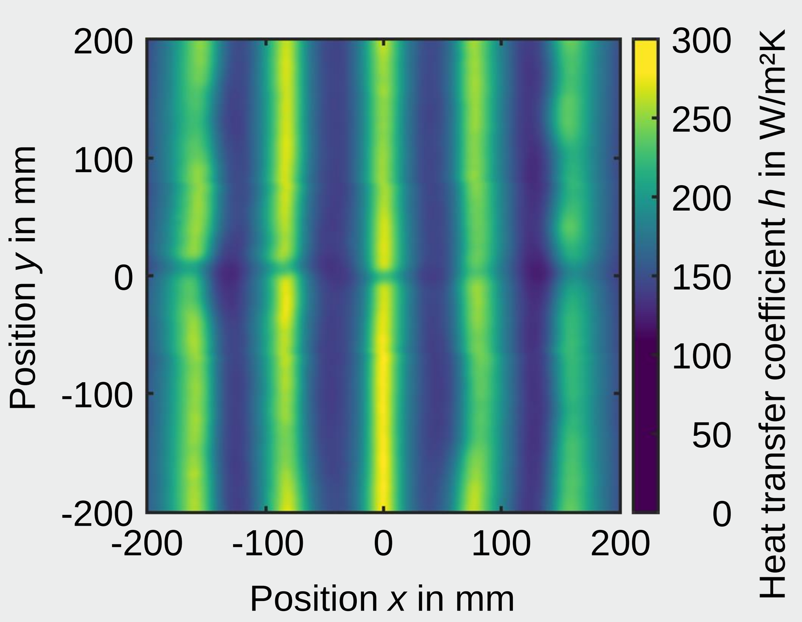

Figure 5: Heat transfer coefficient distribution of a slot nozzle array

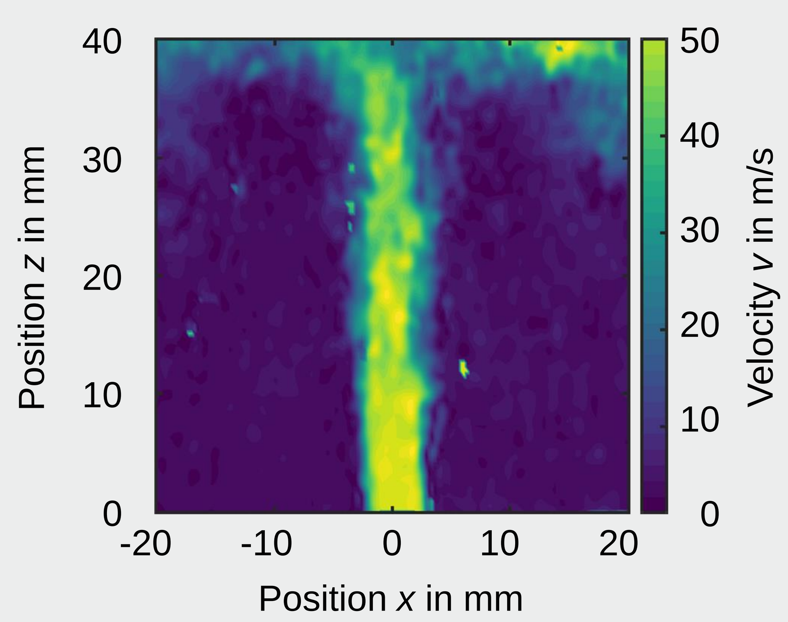

Figure 6: PIV snapshot of the velocity field

Contact
Eileen Trampe, M.Sc.
+49 (0) 241 80-26051
trampe@iob.rwth-aachen.de
www.iob.rwth-aachen.de

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

IOB Department for Industrial Furnaces and Heat Engineering
RWTH AACHEN UNIVERSITY