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Review

Pulsating and Synthetic Impinging Jets

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Abstract : This is the second part of a survey summarizing authors' research over a period of two decades on enhancing impinging jet heat and/or mass transfer by periodic unsteadiness of nozzle flow rate. The first part, Tesař and Trávníček (2004 b), identified the reasons why pulsation does not always improve the transfer rate: the pulses do not reach up to the wall. The authors nevertheless demonstrate a transfer rate improvement, but in flows with inherent instability found in annular impinging jet. The excitation there causes a topological metamorphosis (reversal of flow character). Also in the extreme case of the synthetic (zero time-mean flow) jets the authors demonstrated a substantial improvement with the annular nozzle. The new approaches presented in the paper offer increased performance of drying and heating/cooling systems, in particular in microdevices with otherwise low or absent levels of natural jet turbulence.

Keywords : Visualization, Unsteady jets, Periodic jet flows, Synthetic jets.

1. Introduction

If the highest possible heat and/or mass transfer rate between a fluid and solid walls is required, the most efficient solution is to use impinging jets. They are currently of increasing importance in applications at small scales, in particular cooling the heat generating microdevices (e.g. computer microprocessors or exothermic chemical microreactors), where the main problem are low Reynolds numbers leading to weak or even absent turbulence.

The basic goal in convective transport is to bring the cooling (or heating) fluid as near to the wall as possible. Impinging jets achieve their exceptionally high transfer rates due to the perpendicular orientation of the flow – accelerated in a nozzle - towards the wall so that it gets nearer to the wall than other flows. Nevertheless, an insulating layer of stagnant fluid, often extremely thin, remains inevitably held at the wall by viscosity. The conductive transport across this layer is usually the main part of overall thermal resistance.

In their previous paper, present authors (Tesař and Trávníček, 2004b) discussed destroying the conduction layer by periodic pulsation of the supply flow. Unfortunately, other researchers (e.g. Herman, 2000) did not find the expected improvement. The near-wall layer exhibits a strong and selective damping capability (Tesař, 1998c), enabling it to absorb and dissipate improperly adjusted oscillation. Also, instead of acting on the conduction layer, pulsation energy may be spent uselessly (Tesař and Trávníček, 2004a) on formation of vortical structures in the jet mixing layers immediately downstream from the nozzle exit. After many tests, positive effect was found by Trávníček and Tesař (2004) with collaborators (Tesař et al., 2001b, 2002), but only in impinging jet configurations exhibiting inherent hydrodynamic instability.

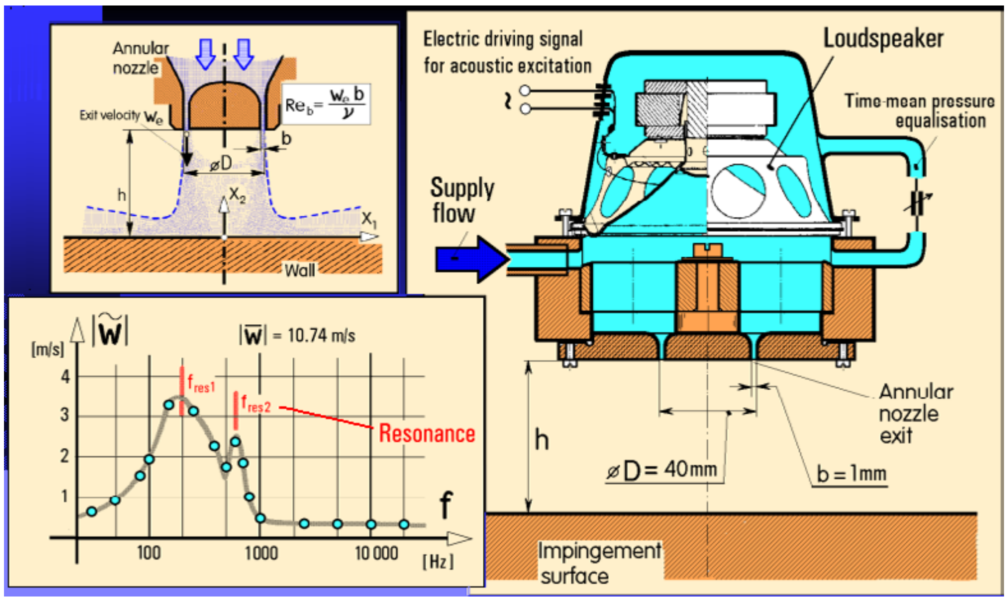


Fig. 1. Annular nozzle used in experiments with varicose excitation and its acoustic resonance properties.

2. Change of Vortical Structure in an Annular Impinging Jet

A flow with the instability, reacting by large-scale changes to even small-amplitude excitation was found in the case of annular impinging jet. Its flowfield is dominated by an annular vortex which, in a certain range of wall distances, responds to the excitation by a change in character associated with heat or mass transfer increase (Tesař and Trávníček, 2004a). This was demonstrated with the annular nozzle of Fig. 1 (note the used cylindrical co-ordinate system: X_1 – radial, X_2 – distance from the wall). The nozzle had small slit width b, only 0.025 multiples of the nozzle outer diameter D. The excitation mode was the varicose (axial) one, using the woofer loudspeaker placed in the space upstream from the nozzle exit. This brings complications with acoustic resonance in this space. Fortunately, the two resonant maxima (Fig. 1) were at the right frequencies for demonstrating the transfer intensification effect. The response of the basic (non-impinging) annular jet to the varicose excitations is shown in Figs. 2 and 3. With the impingement wall in suitable range of distances ($h = 0.5\ D$ to $1\ D$), the vortex ring of the “centripetal” regime is elongated into an unstable “bottleneck” (Tesař and Trávníček 2004b). This flow configuration exhibits the desired response to excitation, as was detected by

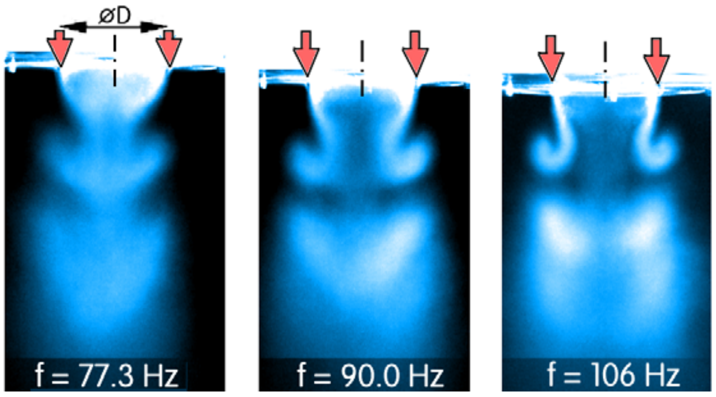


Fig. 2. Effect of excitation frequency on the large-scale vortical structure of an annular jet. Smoke-wire visualized flow photographed by multiple exposures, phase-locked to excitation. Low Strouhal numbers from Sh = 0.28 (f = 77.3 Hz) to Sh = 0.38 (f = 106 Hz), $Re_D = 28600$, $Re_b = 715$. Very large nozzle-to wall distance.

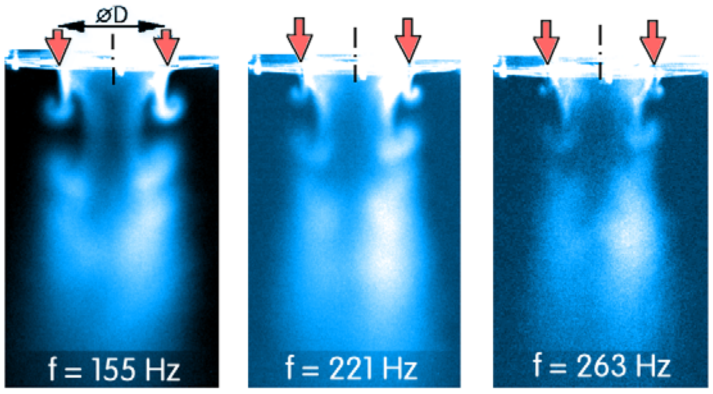


Fig. 3. Multiple-exposure photographs of the excited annular jet at higher Strouhal numbers from Sh = 0.56 (f = 155 Hz) to Sh = 0.94 (f = 263 Hz), Re_D = 28600, Re_b = 715. Very large nozzle-to wall distance.

hot-wire probe measuring at a small distance above the wall the absolute magnitude $|\mathbf{w}|$ of the velocity vector **w**, resolved into time-mean $|\overline{\mathbf{w}}|$ and fluctuating component. The latter is characterized in Fig. 4. by its root-mean-square value $|\tilde{\mathbf{w}}|$. The desirable effect in these experiments was an increase in the level of the fluctuating velocity at the wall, the radial distribution of which is plotted in the bottom parts of Fig. 4. The increase is expected to lead to higher turbulent momentum transport and, on the strength of Prandtl's analogy, higher convective transfer rate. The effect depends on excitation frequency. In the example **a** in Fig. 4, the rather high frequency was chosen to correspond to the Strouhal number of plane jet varicose instability evaluated for the nozzle width b**.** Despite this and despite the wall distance corresponding to the unstable annular jet configuration, no response to the excitation could be detected. At another, lower frequency case **b**, Fig. 4, the anemometric measurements have shown a considerable effect of pulsation on the time-mean flowfield, switching it from "centrifugal" into the "centripetal" regime of near-wall streamlines (note the velocity minimum moved away from the jet axis). Only at even lower frequencies, 100 Hz and 50 Hz (**c** in Fig. 4) the welcome increase (more than three-fold in some locations) of the fluctuations at the vicinity of the wall could be demonstrated. It was again associated with reversal of the near-wall flow (Trávníček and Tesař, 2004b) – as shown in Fig. 6. The resultant intensification of the convective transport was evaluated by the naphthalene sublimation mass transfer measurements,

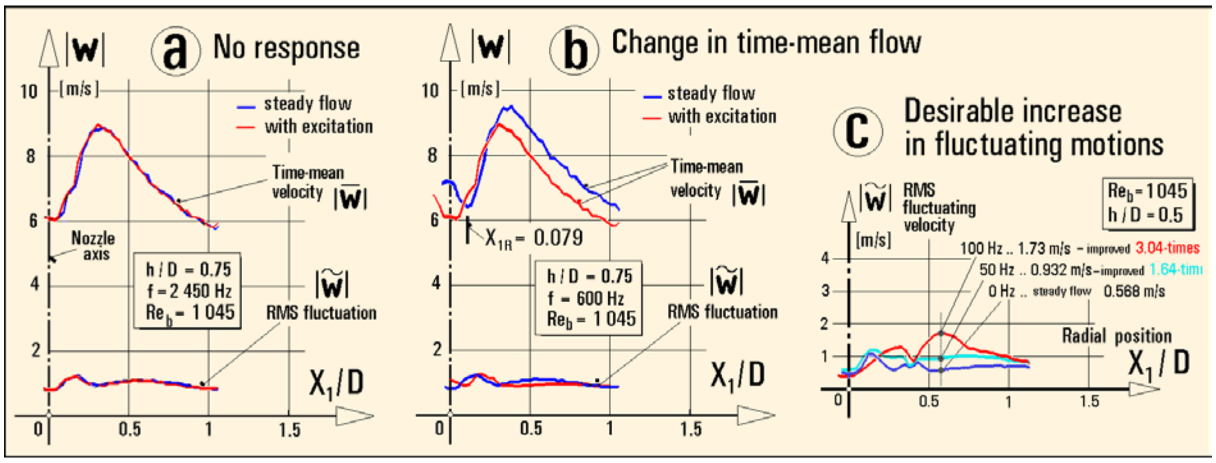


Fig. 4. Radial distributions of time-mean and fluctuating velocity along the wall showing the responses of an impinging annular jet to superimposed varicose oscillation: a) No effect at all, b) change in character of time-mean flow, c) Increase of fluctuating velocity. Measured by hot-wire anemometer – Tesař et al., (2001b).

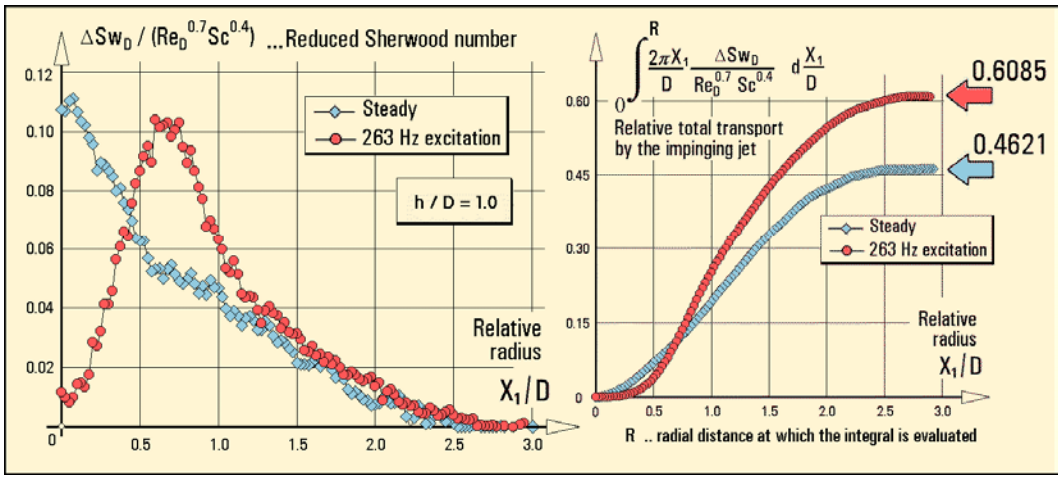


Fig. 5. Change in the distribution of mass transfer intensity on the wall due to excitation of the annular impinging jet, measured by naphthalene sublimation method. Re_D = 28 600, Re_b = 715. The integrals at right show the resultant overall transfer across the whole impingement “footprint” increases by 32 %.

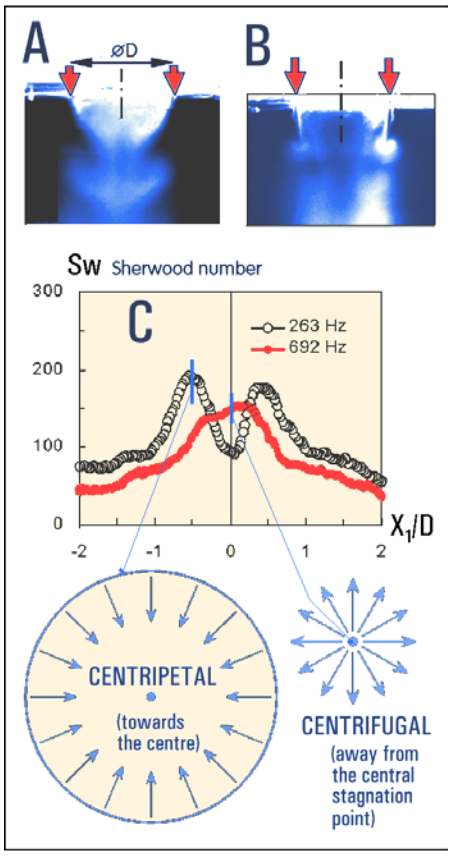


Fig. 6. Acoustic excitation at and near the unstable configuration (here shown for the two resonant maxima from Fig. 1) can cause a metamorphosis of the wall flow under the annular impinging jet, a reversal of the flow direction to or from the axial stagnation point.

Figs. 5, 6, 7, and 8. More relevant than the local increase in transport coefficient (nondimensionalised as Sherwood number in this mass transfer case) is the integral across the whole transfer surface - an example at right in Fig. 5 emphasises the importance of the larger annular area on which the increase takes place, making insignificant the actual decrease near the jet axis. The changes were measured and presented as an effect of the excitation frequency, since the loudspeaker driving power was kept constant. However, the resonant character of the acoustic processes upstream from the nozzle (Fig. 1) links the variation of frequency with amplitude changes. It is thus not surprising that the most apparent changes between A and B in Fig. 6, (differing in the resultant flowfield topology, shown in diagram C) – and also in the convective transport effects – were found at the two frequencies corresponding to the amplitude maxima due to resonance in Fig. 1.

3. Flow Reversal, Synthetic Jets

The fact that most apparent changes were obtained with the largest excitation amplitudes has led to an interest in the large-amplitude excitations. Of particular concern were flows in which the flow velocity passes through zero at an instant of the oscillation cycle. Since thickness of the stagnant wall layer requires some time to grow (in laminar regime the thickness is proportional to $\sqrt{t}$), transfer rate improvement may be in principle obtained by stopping the flow at an instant of the cycle. This causes the conduction layer to begin growing anew, never

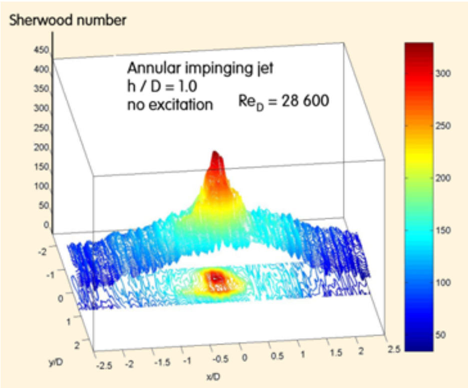


Fig. 7. Distribution of the local diffusion rate from the surface measured by the naphthalene sublimation method under an annular impinging jet.

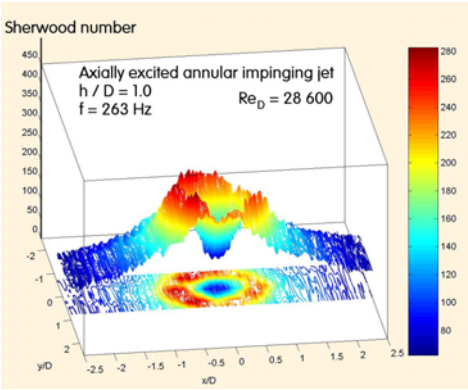


Fig. 8. The effect of superimposed excitation on the distribution of the local diffusion transport rate under the same conditions as in the previous Fig. 7.

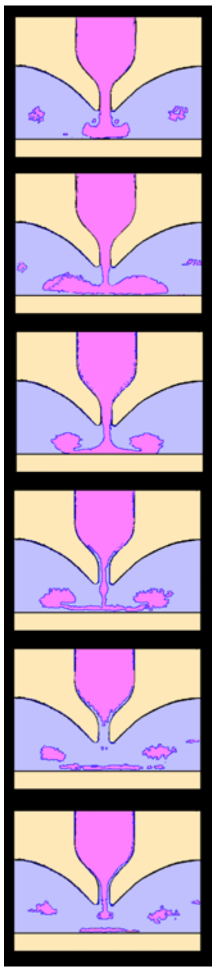


Fig. 9. Posterized video frames of impinging jet with pulsation so strong that the nozzle velocity for a part of oscillation period temporarily reverses sign.

allowing it to reach large thickness. The extreme case are the synthetic jets with flow reversal during each cycle and zero time-mean nozzle flow rate, as studied already by Tesař, 1983 (cf. also Tesař and Zhong, 2003). The term “synthetic” jets, conveying the idea of their being synthesized from individual vortex rings - which is actually true only for some regimes, Fig. 10 - was introduced later by Glezer, 2002. Synthetic jets have the practical advantage of simpler overall system, requiring neither central blower nor the fluid transport pipelines, which occupy too much space in conventional arrangement of cooling at a number of locations. An instructive insight into the behaviour of the large-amplitude jets with the nozzle flow reversal was obtained by video recordings of planar impinging jets between transparent parallel enclosures, Fig. 9. The frames were processed by posterization – a drastic reduction of the depth of colour palette, in Fig. 9 to only two colours. This made possible following clearly the fate of each flow pulse fluid. An interesting aspect is the “lift-off” of a part of the flow pulse remainders (seen in the last two frames and those from previous pulse in the first two frames), which do not move along the wall but tend to rise above it. There is little doubt this being the action of the dominant vortices - in analogy with the similar effect in steady flow shown in Tesař and Barker 2002 – with consequent loss of heat or mass transfer efficiency at locations away from the impact area. Even more important in the present context, however, is the fate of the other part of the pulse fluid. It undergoes a disappointing “splatter”, formation of a layer covering the wall and separating it from the effect of velocity reversal above. This is seen in the last two frames.

Nevertheless, effectiveness of the convective transfer effects of impinging synthetic jets could be demonstrated – but again, however, with the annular nozzle, after disappointing results with simple round nozzle. Figure 11 shows distribution over the impingement surface of mass transfer obtained again by the naphthalene sublimation measurements for synthetic jet issuing from the same nozzle under roughly identical conditions as in the pulsed jet Fig. 8.

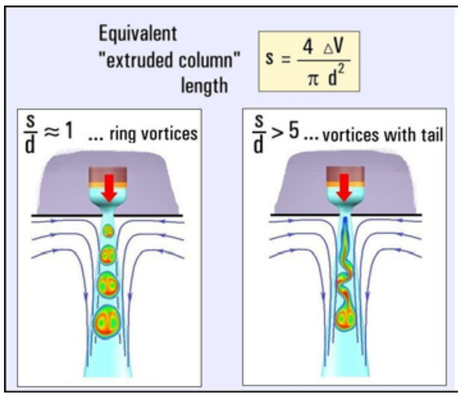


Fig. 10. Two basic cases of the synthetic jet, produced by rectification effects in alternating nozzle flow.

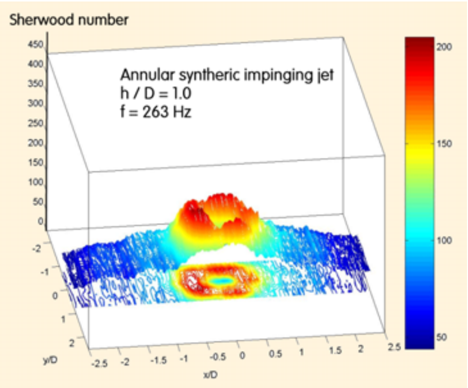


Fig. 11. Distribution of the local transport rate under an annular synthetic (zero time-mean component) jet under conditions corresponding to Fig. 8.

(Trávníček and Tesař, 2003) Despite the substantial saving of the driving effort due to the absence of the time-mean flow component, the values of the transfer coefficients are not much lower than in the excited steady flow case in Fig. 9.

4. "Hybrid-Synthetic" Jets

The obvious disadvantage of synthetic jets in the heat and mass transfer applications is the re-ingestion of fluid that has already performed its pass over the transfer surface so that its state was already changed - in the cooling application it is the re-ingestion of the coolant already heated by its flow in the proximity of the hot surface. This fluid needs first an opportunity to regenerate before it can be used again. In the cooling application it has to be moved away from the impinging flow region so that it can cool down. What is needed is arranging a sufficiently long circulation path for the fluid leaving the transfer surface before it can get back near to the ingesting nozzle to be again accelerated towards the wall. For air as the coolant this path may involve the atmosphere, with its virtually unlimited cooling capacity. The generation of the flow in the recirculation loop may be arranged using the principles of the no-moving-part pumping (e.g. Tesař and Peszynski 2003). Available basic principles may be divided into two groups:

a) Layouts with recirculating entrained fluid and pure synthetic jets (zero-time-mean nozzle flow), using the fact that synthetic jets ingest back into the nozzle mostly fluid from the vicinity of their nozzle exit (Fig. 12), which may be separated by a partition (Fig. 13) from the space nearer to the heat exchanging wall.

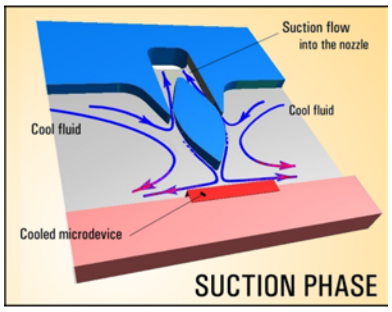


Fig. 12. The suction phase in the tested impinging synthetic jet with centerbody leading it towards the cooled object while the sucked in fluid is a cooler one from locations further away.

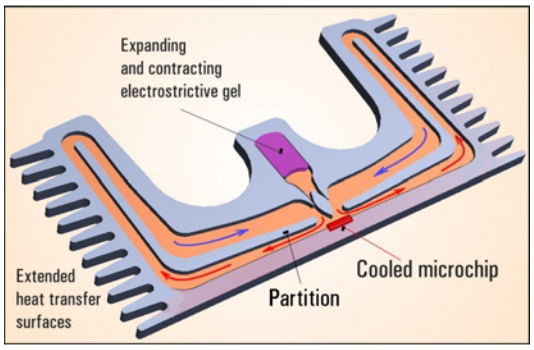
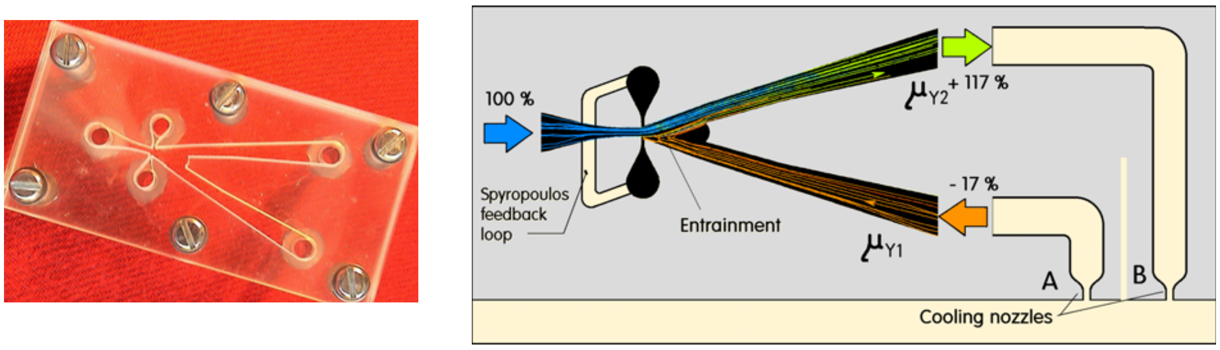


Fig. 13. Synthetic-jet driven coolant circulation loops. The core part correspond to Fig. 12, the partition between the cold and heated fluid converts it into a fluidically pumped circulation loop.



Figs. 14. and 15. Fluidic oscillator laboratory model and computed pathlines showing the reverse flow back into cooling nozzle A due to the entrainment into the switched jet.

b) The "hybrid synthetic jets" with the replacement fluid passing through a one-direction valve (= fluidic diode) into the displacement volume of the actuator. A recently tested example is described in Trávníček et al. (2004). The tested configuration uses the rectification effect of a diffuser, particularly suited flow for microdevice size (although the tested laboratory model is quite large). Time-mean value of the nozzle exit flow is non-zero.

The same effect – non-zero time-mean flow rate – may be also obtained with fluidic oscillators consisting of a jet-type diverting amplifier provided with suitable feedback loop. Figures 14 and 15 present a currently tested example with a pair of jet-generating nozzles. The return flow into each nozzle is due to the jet-pumping entrainment effect of the main switched jet inside the amplifier. A distance between the nozzles of the pair prevents the aerodynamic short-circuiting that limits the effectiveness of e.g. coaxial exit layouts (Trávníček et al., 2004).

The synthetic jets (Fig. 13) may be directly driven by an electric signal, in recently tested versions by electrostritive gels (Lehman 2001) while the fluidic oscillator (Fig. 15) needs an external fluid source and the supply piping – which, however, is needed anyway in high thermally loaded systems, where the short closed regeneration loops like the one in Fig. 13 does not suffice.

5. Conclusions

Desirable improvement in cooling/heating and/or drying performance of impinging jets may be obtained by generating periodic unsteadiness – in a range from small disturbances up to the flow reversals in synthetic and hybrid jets. It is necessary to avoid spending the excitation energy on formation of unwanted vortical structures. This may require special nozzle configuration, of which the annular nozzle is an example. The necessity of replacing the working fluid limits the applicability of (otherwise advantageous – no fluid distributing pipelines) pure synthetic jets. For really extremely high heat and mass transfer rates the most hopeful are the "hybrid" jets - a combination of the synthetic jet with fluidic pumping.

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