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PHASE-SYNCHRONISED INVESTIGATIONS OF TRIGGERED VORTICES IN IMPINGING JETS

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Summary: *Impinging jets can transfer the highest achievable thermal flux into (or out from) solid bodies. The transport is significantly influenced by complex and so far not fully understood vortical structures that develop due to hydrodynamic instability. This contribution describes experiments with visualisation of impinging air jets in which periodic formation of vortices was triggered by azimuthal travelling waves generated in nozzle exit - and was phase-synchronised with the camera. Visualisation was by laser light scattered from water mist particles added to the supplied air. The instability structures were identified in the images by using their coherence.*

1. Introduction

Jets impinging upon a solid body, Fig. 1, are of particular importance for heat transfer applications, because they can achieve the highest thermal power transfer rates – higher than any other convection transfer configurations.

It has been recognized for quite a long time (cf., e.g., Meola, deLuca, and Carlomagno 1996) that impinging flows and the resultant heat transfer properties are strongly influenced by vortical motions in the jet. The motions arise and develop due to hydrodynamic instabilities – both those of the jet as a whole and those caused by instability of the mixing layer

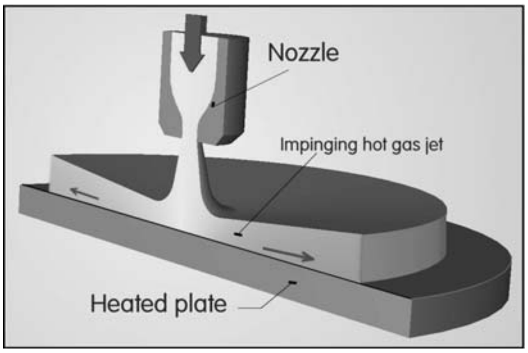

Figure 1 Schematic representation of an impinging jet of hot gas heating a plate

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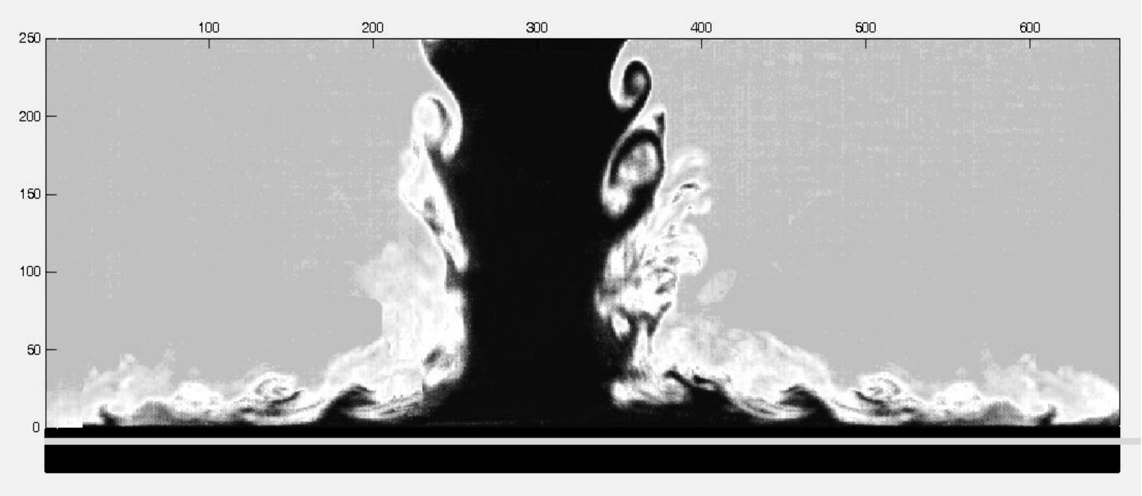

Figure 2 Distribution of fog particles concentration in a typical the investigated impinging jet as revealed by the intensity of scattered laser light. Reynolds number Re = 10 200. Clearly distinguishable are the vortical structures in the mixing layer.

surrounding the jet core. In the photograph of an example of visualised impinging jet, photographed by the authors and presented in Fig. 2, the vortical structures in the mixing layer are immediately apparent to be important – and, in fact, dominant features of the flowfield.

All aspects of the role of the instabilities in impinging jets have not been so far fully elucidated. For example, it is a well known fact that experimental results obtained with the nozzles positioned at a small relative distance (equal to about 2 diameters) above the impingement wall exhibit strange off-axis transfer rate maxima on the wall (Tesař 1998). These, according to general consensus, are caused by the vortical motions (e.g. Meola, de Luca, and Carlomagno 1996, Tesar and Barker 2002, Vejražka a Tihon 2005). However, details of the mechanism generating the maxima are not fully understood.

Theory of the instabilities is complex and still not completely developed. This is why investigations of the vortical objects have to be mainly done by laboratory experiments. These are also rather difficult. The main problem encountered is the vague and indistinct character of structure boundaries (which are irregular and far from sharp and clear) and the structures' relatively fast motion and variation in time. The structures appear in the flow with certain periodicity, but at a chaotic phase. This makes identification of structures in different periods quite uncertain. Particularly troublesome problem is the influence of chaotic turbulence by which the structures are surrounded and within which they finally disappear.

The authors made three important steps in their experimental investigations, aimed at flow visualisation, in an attempt to acquire the experimental data on the structures in a manner making easier the processing of the images.

a) Application of a periodic triggering action, which causes the vortices to be formed with precisely reproducible periodicity.

b) Synchronisation of the vortex formation triggering, at an adjustable phase angle, with the instants at which the camera recorded the pictures of the visualised jet.

c) The acquired visualisation images are processed in a new manner, which makes apparent and easily recognisable the instability structures by utilising their higher coherence in contrast to the uncorrelated surrounding turbulence.

2. Experiment

2.1. General features

The investigated air jet was generated in a d = 40 mm i.d. nozzle located in the centre of a large horizontal surface perpendicular to the jet axis. The jet impinged upon a parallel impingement surface positioned at a distance h = 100 mm, i.e. at relative height equal to 2.5 nozzle diameters.

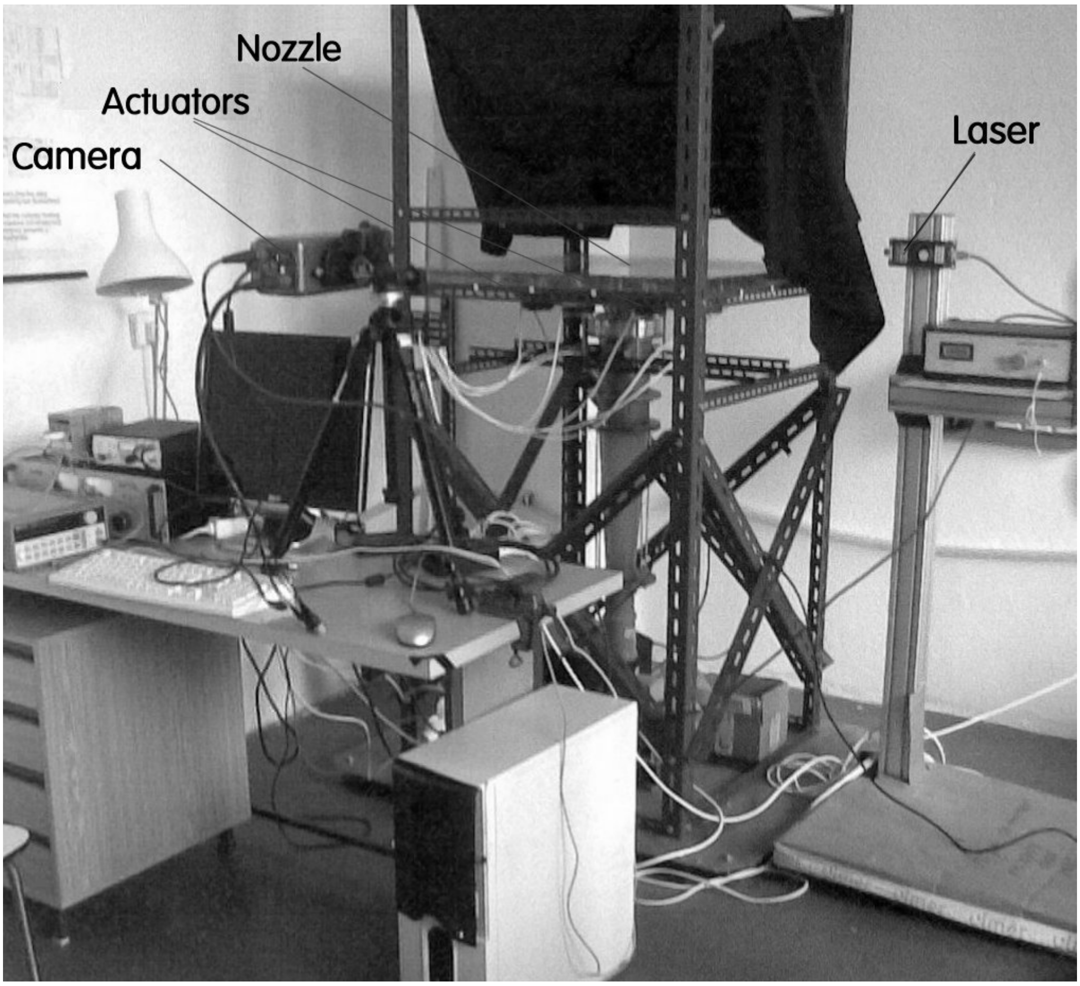

Figure 3 Photograph of the experimental rig. The black curtain – here shown lifted – surrounds the investigated jet for laser light safety reasons.

Compared with standard pictures of impinging jets, the arrangement of the test rig was vertically inverted: the flow from the nozzle was directed vertically upwards and impinged upon the impingement plate held above the nozzle.

The air was supplied into the nozzle by an adjustable-speed blower. It passed through a settling chamber that was inside provided with two flow stabilising sieves in series. The blower flow rate could be varied so that Reynolds numbers of the jet could be adjusted in the range of the order $1 .10^3 – 10 .10^3$. Most experiments were actually made near the upper limit of this range. The jet was visualised by addition of water mist particles. These were generated by evaporation of water and passing the vapour/air mixture through a chamber filled with crushed ice, in which the water vapour condensed to form the mist. This was injected into the inlet of the blower, as seen in Fig. 4, so that the blower impeller could well mix the mist with the additional air that entered the blower directly from the atmosphere.

The jet was illuminated by the "laser knife" – a light sheet produced by cylindrical optics. The images of the scattered light were captured by a digital camera the lens axis of which was oriented perpendicularly to the light sheet. Essentially, the intensity of the scattered light captured in a particular location in the frame contained information about the local concentration of the mist particles. The laser a diode-pumped solid state green light (wavelength 532 nm) Nd:YAG laser DPGL-2200L-45 supplied by Shanghai Uniwave Technology Ltd. Its maximum output power is 200 mW. The optics generated the light sheet of fan angle 45° and guaranteed width < 5 mm at 5 m distance.

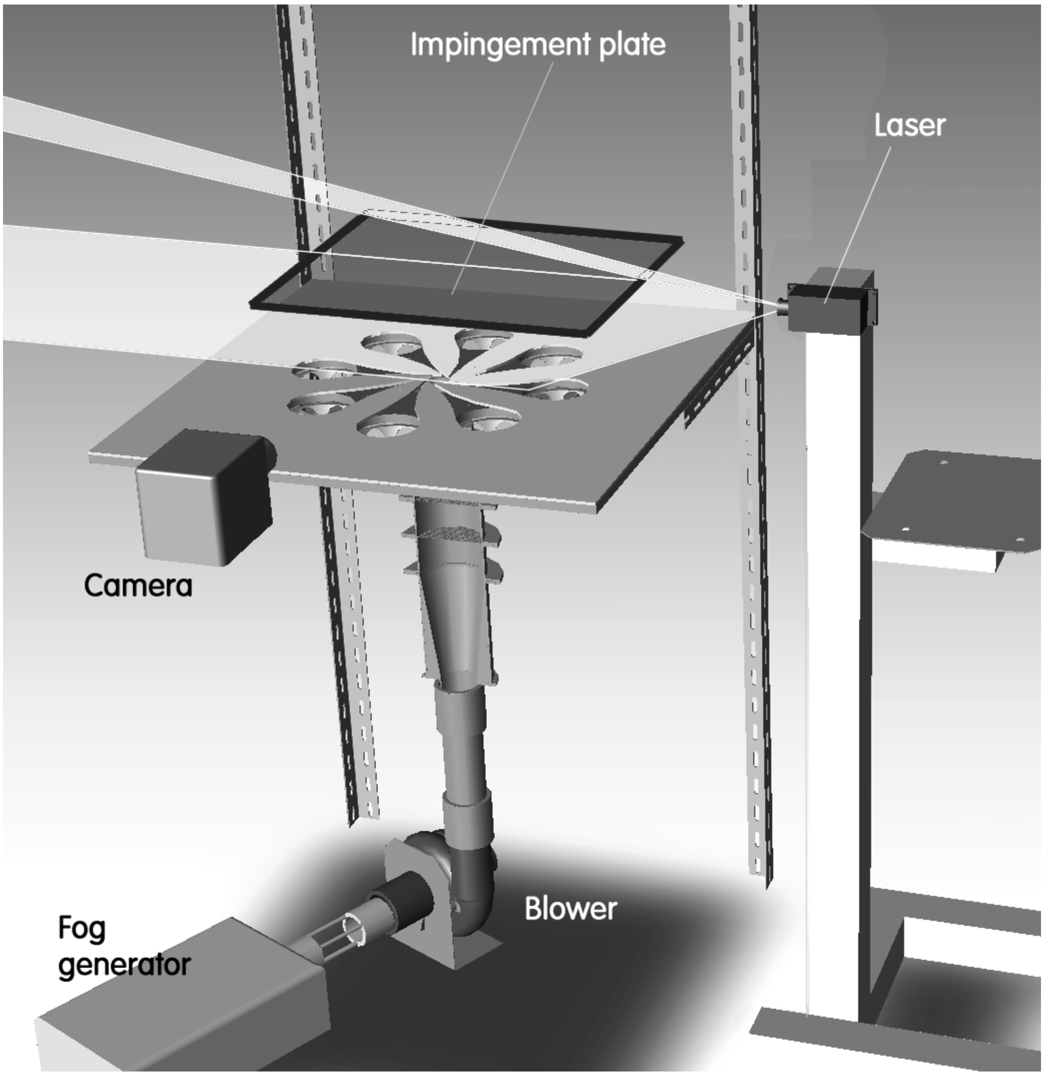

Figure 4 Partly cut-off drawing of the experimental rig. The experiment is actually vertically inverted relative to the standard images of impinging jets: here the jet issues from the nozzle vertically upwards and impinges upon the plate that is held above the nozzle.

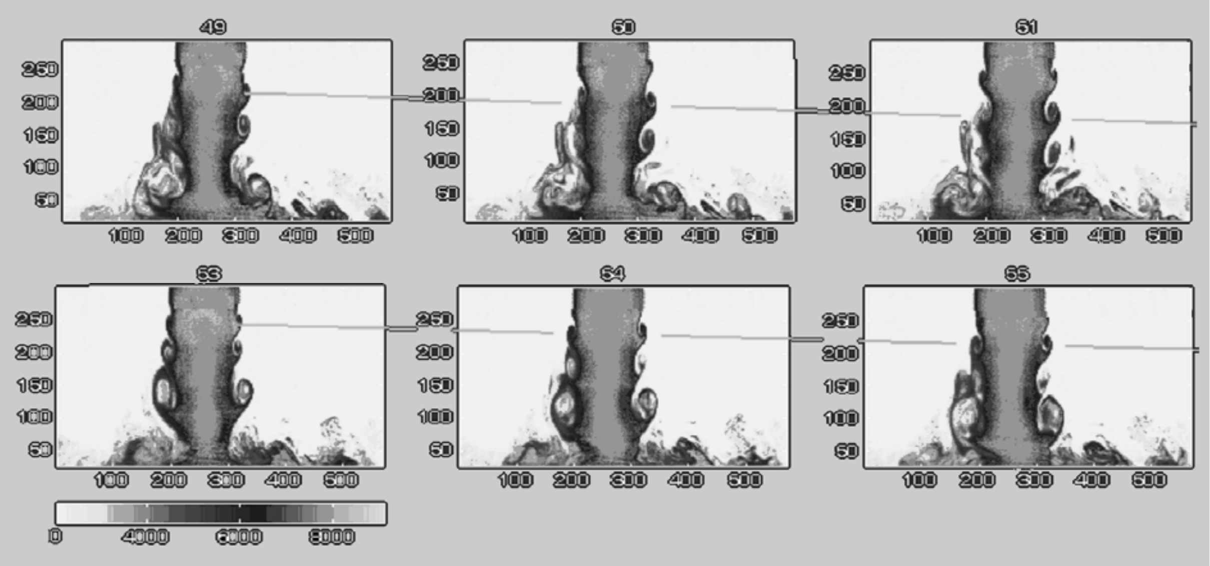

Figure 5 A typical sequence of video frames of un-excited impinging jet. The actually photographed various levels of scattered light intensity were converted into colour assigned according to the scale at bottom left. The inclined line connects the positions of a particular vortex as it progresses towards the wall.

The camera we used was Vision Research Phantom v7.3 with continuously recording 14-bit monochrome SR-CMOS sensors giving 800 x 600 pixels resolution and top speed of 6 688 frames per second – which was not used in the present case.

In the example pictures of unexcited jet presented in Fig. 5 the frame acquisition speed was 100 frames per second. The original monochrome pictures presented just various levels of grey. The entrained outer air containing no mist droplets appeared black so that ideally the numerical value stored for the corresponding pixel of the image should be 0. There is always some inevitable light dispersion inside the test space and also the absorbance of the background (which was black textile – the curtain from Fig. 2) was not perfect, so that the minimum values are higher. On the other hand, no pictures contained the full 14 bit white extreme. Also the camera sensitivity (adjustable from the camera-control software) was never set so as to utilise the full 14 bit resolution. As a result, instead of the theoretical range 0 to 16 384, in practical situations the pixel values were in a more narrow range. This was shifted down so as to make the lowest value exactly zero. Typically, after the shift, the highest value were typically near to 9 000. This is seen in the colour coding bar in the lower left corner of Fig. 5. To facilitate visual inspection of the images, the levels of grey were then replaced by a false colour using an assignment function which could be completely arbitrary – it is presented in the accompanying illustrations by the colourbars always positioned in the images.

2.2. Phase synchronised recording

Among the complicating factors that make any closer study of the vortical structures so difficult, the key problem is their motion. The basic movements are due to the convective translation from the nozzle towards the impingement wall, as it is clearly recognisable from the slope of the inclined line connecting positions of the same vortex in Fig. 5. In the phase-

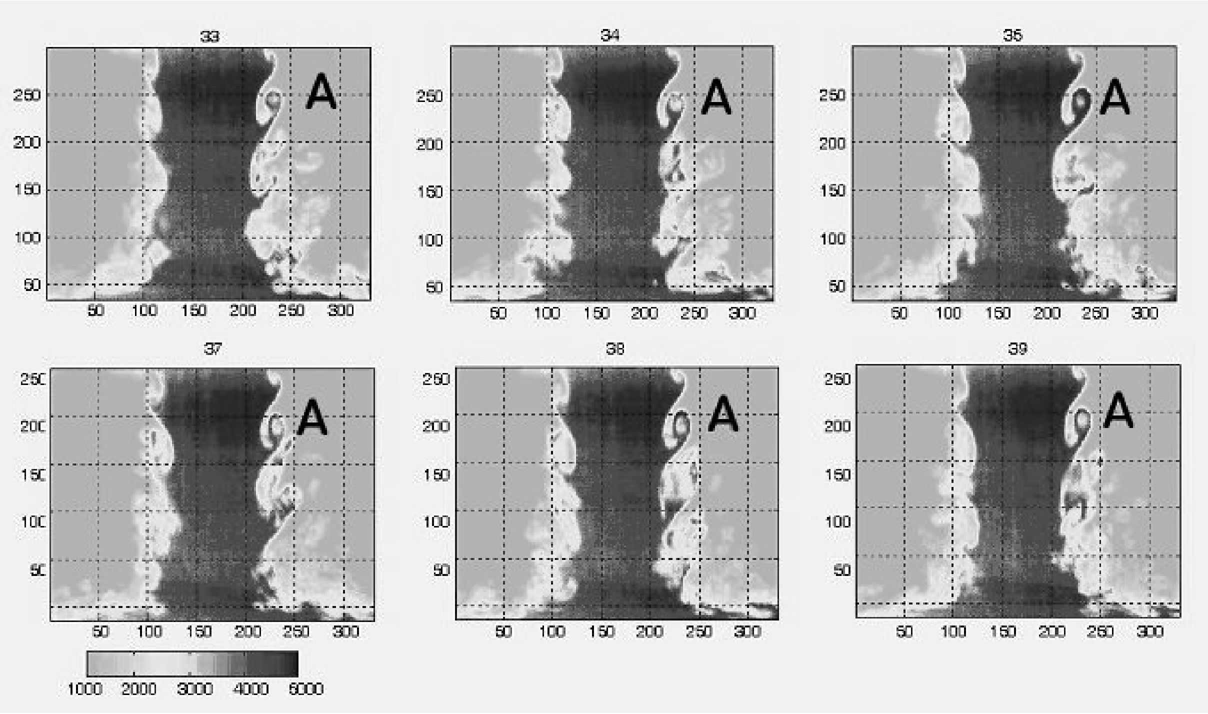

Figure 6 An example demonstrating the synchronization. The camera release was activated at the same phase of the excitation signal. Different vortices, labeled A, appear at the same location in the frames and when the sequence is seen as a video clip, these vortices appear due to the stroboscopic effect as if they were a single stationary object.

synchronised recording and triggering formation of new structures, it is possible to virtually "stop" this motion. It is essentially the stroboscopic effect: the pictures are taken always at exactly the same phase of the periodic process of their development. Of course, in such conditions of the vortices virtually prevented to move it is much easier to investigate the

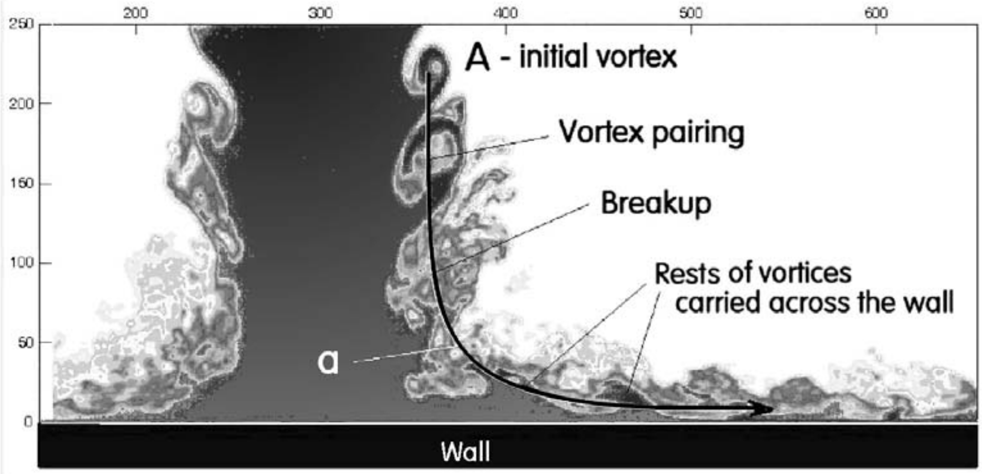

Figure 7 The constant-phase picture-taking – together with colour-coded processing the features identifiable in the frames – makes possible a close study of the development of the structure as it progresses along the mixing layer and gradually decomposes into turbulence.

dynamics of their development and later their decomposition into turbulence. Because the main periodic component of the motion of the structures keeps them at a particular location in the frame, it is possible – by evaluating the phase average and deviations from it - the uncorrelated components of their behaviour. A single-picture example that demonstrates the possibilities offered for the study of the breaking-up of the vortices by this synchronisation is presented in Figure 7.

With natural generation of vortices only very roughly periodic, the stroboscopic effect would not work without the triggering. The periodicity has to be secured by giving each newly formed vortex a precise signal for starting its evolution. Due to the triggering, an essential part of the experimental rig developed for this purpose is a system of actuators for periodic excitation of the jet flow. It should be stressed that the actuators do not generate the vortices – which would be generated even without the excitation. What is done is just to induce the beginning of the formation by a disturbance that is energetically very weak. Because of maintaining a precise excitation frequency and phase, the stroboscopic effect makes the pictures of subsequently appearing vortices to look like if there were permanently only a single, stationary vortex – as is, e.g., the vortex A in Figure 8 above on this page.

In Figure 7, which is an enlarged frame from another sequence, is shown an example of the “frozen” vortices in the mixing layer of an impinging jet. The vortices in reality move along the pathline “a”, but the synchronisation makes possible virtually “stopping” them – in reality showing different vortices but at equal stage of their development. Apart from the possibility to study them in detail, this also makes possible comparing their changes in appearance from period to period – an invaluable tool for identifying the key features of the decomposition and final disappearance in the surrounding turbulence.

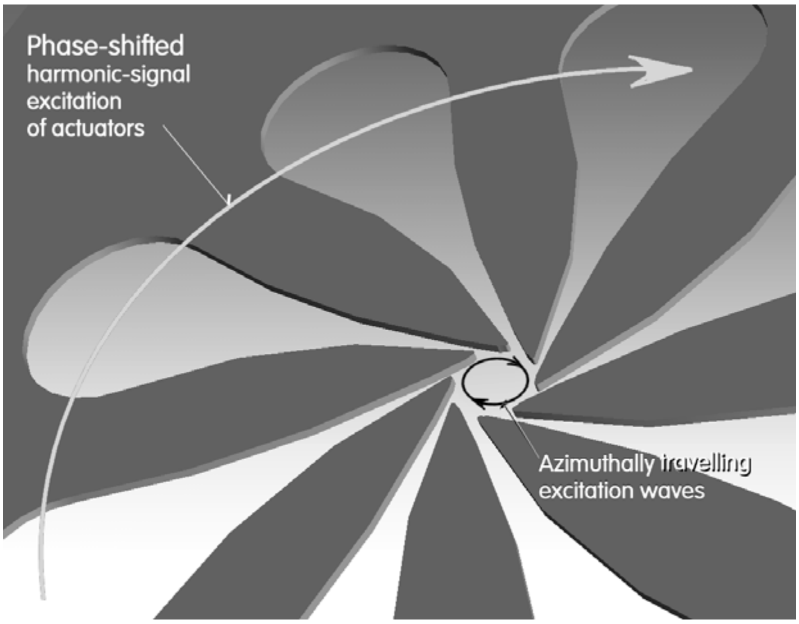

Figure 8 The idea of generation of the azimuthal travelling wave in the nozzle exit plane triggering formation of instability structures in the mixing layer of the jet. In co-operation of the jet flow perpendicular to the plane of azimuthal motion, the actuators produce two helical structures per excitation period.

2.3. Azimuthal excitation waves

The vortical structures form helices with the axis coincident with the axis of the nozzle. Helical structures exhibit several rather unusual and even paradoxical properties – like an inverse direction of spectral energy transport, as discussed, e.g., by Levich and Tsinober 1983, Moiseev et. al. 1983, Druzhinin and Khomenko 1991, or Tesař, Zimmerman, and Regunath 2005. Obtaining information about these properties is the ultimate target of the investigations. In particular, we wish to learn more about the processes taking place when two helical structures meet and interact – Tesař, Zimmerman, and Regunath 2005. The experiment is therefore set up with an aim is to generate two structures chasing one another. This is why the chosen excitation mode in the experiments is azimuthal, acting on the jet in the plane of the nozzle exit and influencing there the incipient mixing layer – Fig. 8. The triggering action has the form of two waves running, one after another, along the circumference of the nozzle exit. The system producing these waves consists of 8 electro/acoustical actuators – in fact standard commercially available low-frequency woofer loudspeakers ARN-165-01/4, as they are shown in Figure 9. Four neighbouring actuators from this system, supplied by harmonic electric current with proper phase shifting by one quarter of the period generate the first acoustic perturbance wave. The actuators operate in collaboration with the translation motion of the jet flow passing through the nozzle. The azimuthal wave coupled with the axial translation produces a helical object once it leaves the exit of the nozzle. Similarly, the remaining quartet of the loudspeakers produces another wave – and another helical object – phase shifted by 180 deg. The two waves follow one another and this generates two interleaved helical structure objects in the mixing layer of the jet. It should be noted that because of this arrangement, the Strouhal number values Sh are twice as high than if they were simply computed from the given frequency f.

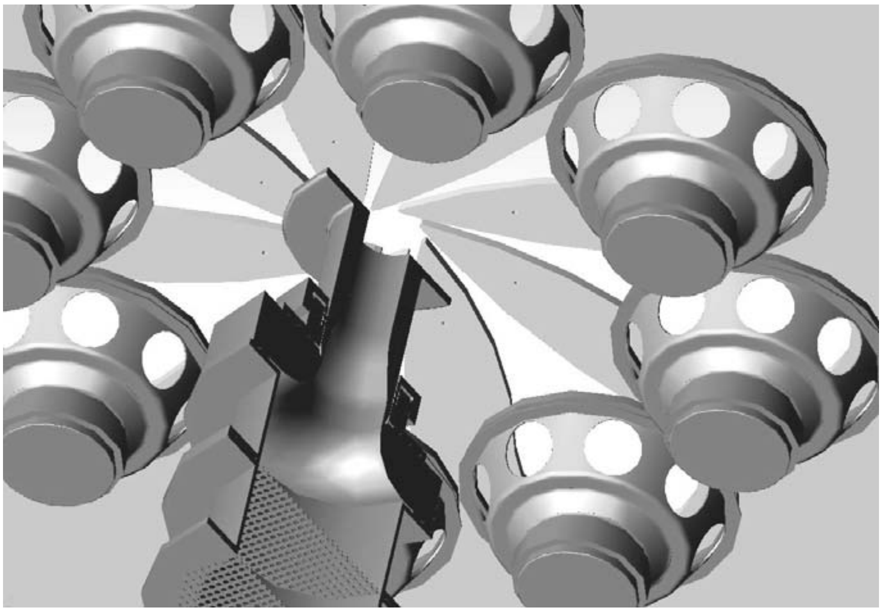

Figure 9 Loudspeakers fixed to the bottom of the nozzle exit plate from below are used as the actuators. Acoustic pressure from them is delivered to the nozzle exit by waveguides with cross-section area decreasing and thus increasing the oscillation amplitude. The nozzle is shown in section, revealing the internal layout with two sieves in the settling chamber.

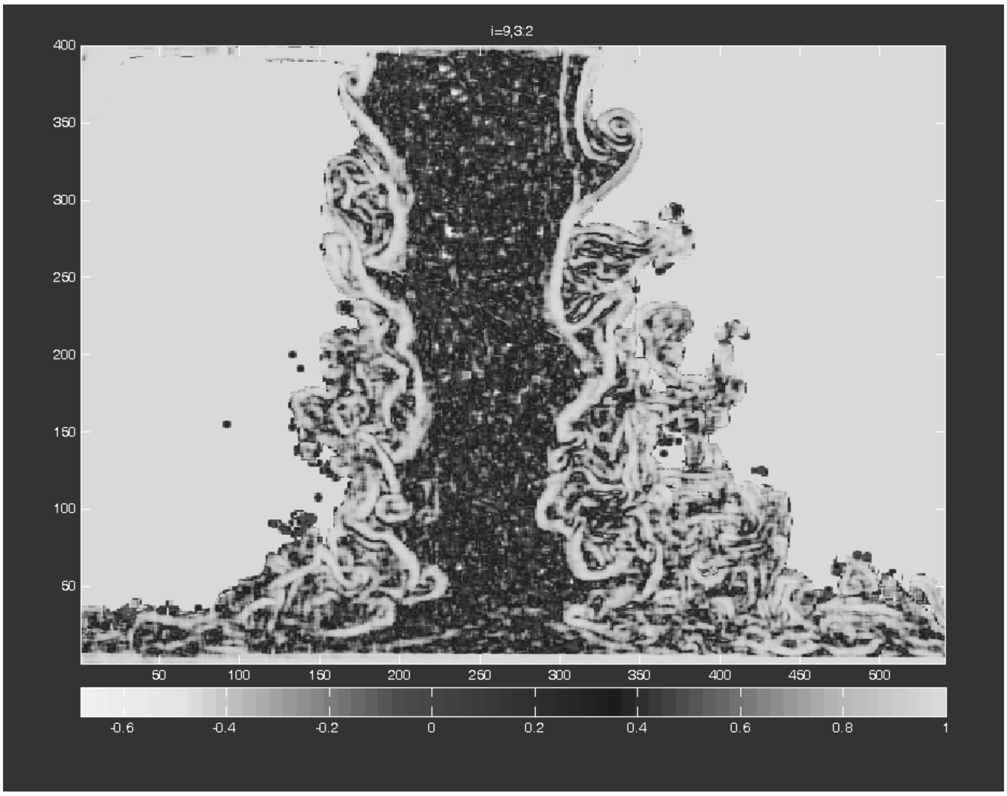

Figure 10 Computed weighted correlations between subsequent frames in a sequence – here for an impinging jet at Reynolds number Re = 8 000 – enhanced the most important features in the visualized flowfield. The extreme values of the correlation coefficient (light coloured) are indicative of the outer contours of moving coherent structures.

3. Image processing

An important part of the discussed project is the rather sophisticated method of processing the image data. In principle, it is a development of the procedures developed (Něnička et al., 2003) for processing visual data from plasmatron research. The key question is identification of the instability structures in the surrounding chaotic turbulence. The main tool is use of correlation techniques, available in standard library procedures for handling matrices. The intensity data of the scattered light captured by the camera are stored as a pixel matrix. For evaluation of correlations is chosen another matrix of the data from the same image sequence. In the computation, in the neighbourhood of each interrogated image pixel – element of one of the matrices – this procedure selects other pixels and places them in a vector. What is then done is essentially computing the normalised value of the scalar product of the two local vectors. This value is the correlation coefficient. Of interest for the identification are the locations exhibiting extreme values of this coefficient – to make these locations more apparent is achieved by assigning to the coefficient values some (false) colour. Initial experience with this procedure, as described by Tesař et al., 2008, was somewhat frustrating in that it tended to generate scattered multicoloured fields. A solution was recently found in computing weighted correlation – by giving less weight to the pixels more distant to the momentarily interrogated position. Suitable weighting function were simple Gaussian distributions. Examples of the resultant pictures of the impinging jet flowfields, for two different magnitudes of the weight factors, are presented in the accompanying Figures 10 and

11. Immediately apparent in them are especially those locations, where the structure, while retaining its general appearance, moves at causes a high negative value of the correlation coefficient at its boundary.

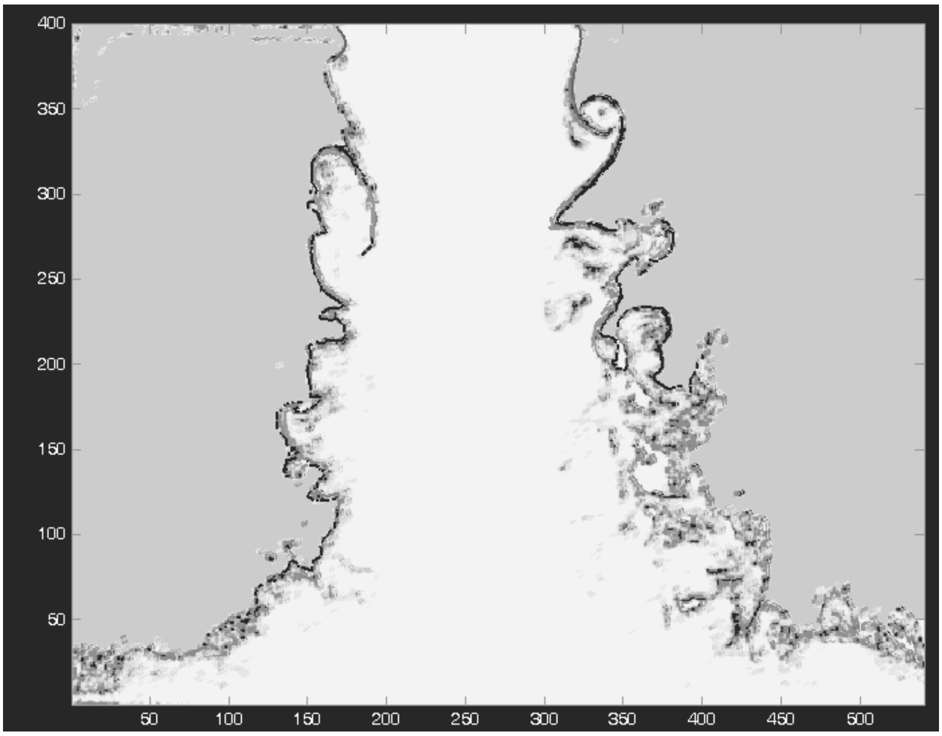

Figure 11 High magnitudes of the applied Gaussian weight factor enhance the outer contours of moving coherent structures in a manner useful for their closer study. Reynolds number Re = 8 000.

4. Conclusions

In this paper, new techniques are introduced for detecting and study of instability structures in impinging jet flows. The fundamental problem is how to extract information about three-dimensional objects – such as the vortical structures – from two-dimensional flow visualisation images. The problem is made more difficult by the objects of interest appearing quasi-periodically (i.e. with large variations in the phase), and moving as they are convected with the flow. Another facet of the problem is the fact that the structures subsequent periods of their quasi-periodic appearance are not identical - due to the stochastic conditions which they encounter in their emergence. The final extremely difficult problem is the structures are submerged in stochastic turbulence – the stochasticity complicates even mere identification of what is a coherent structure. Because of the unsteady character of the detected objects, the turbulence cannot be simply filtered out by statistical averaging.

The discussed approach to solving these problems operates with triggering the vortex formation by a periodic signal from which is derived the picture acquiring by the camera. The signal generating system can also shift the phase of the signal. This way one obtains a frame sequence consisting of a relatively small number of monochrome pictures taken at periodic time intervals, each of them capturing only a plane section through the object. This single plane information is insufficient for a tomographic reconstruction, nevertheless the images may be analysed using as the basic idea for the processing algorithm the difference in the rates of change of the identified object and of the surrounding chaos.

5. Acknowledgement

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