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Visualization and Mass Transfer with a Bistable Two-Slot Impinging Jet

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Abstract : A two-dimensional air impinging jet with a passive control has been studied experimentally, and smoke visualization, measurement of mean flow characteristics, and mass transfer experiments have been performed. Investigated flow field is intrinsically bistable, and two flow patterns exist under the same boundary conditions. The both patterns differ in a "bubble of separated flow", either a small or large recirculation area is embraced inside the jet. A change between flow field patterns is hysteretic in character. The large recirculation area bridges the whole nozzle-to-wall spacing, and seems to be very promising for an augmentation of heat/mass transfer.

Keywords : Visualization, Mass transfer, Impinging jets, Bistability, Naphthalene sublimation

1. Introduction

Heat/mass transfer between a surface and a surrounding fluid is frequently designed as a jet impingement. There are various applications in drying, heating and cooling, where impinging jets are effectively utilized. Numerous studies over the past four decades have dealt with the subject. The most important results were summarized in an outstanding monograph by Dyban and Mazur (1982), and in an exceptional work by Martin (1977). Several comprehensive reviews have appeared periodically up to the present time (e.g., Downs and James, 1987; Jambunathan et al., 1992; Viskanta, 1993; Polat, 1993; Webb and Ma, 1995). A theoretical, experimental and numerical research of the topic continues perpetually – see, e.g., a recent review by Garimella (2000).

The jet is generated in a nozzle, and directed towards an exposed wall. Three significant advantages of impinging jet applications are (1) high intensity of heat/mass transfer, (2) good adaptability to a different surface shape including a good localization of a higher heat/mass transfer area, and (3) relatively simple and cost-effective applications. Very high heat/mass transfer from the exposed wall can be achieved even in the basic geometry cases of round and slot nozzles, nevertheless a typical aim of many present-day investigations is a further augmentation of the heat/mass transfer intensity.

The problem of flow stability is exceptionally topical. It concerns the most fundamental theoretical questions of fluid mechanics such as the problem of the origin and development of turbulence. Moreover, a close mutual connection between the instability and periodic unsteadiness is obvious. These problems are becoming of high importance for various engineering applications – in particular the applications involving heat/mass transfer between solid surfaces and a surrounding fluid.

2. Bistable Impinging Jets

The bistability means an existence of two stationary states. This means the boundary conditions are not sufficient to determine the flow field, and a parameter setup history is basically important. The bistable behavior of impinging jets is typically observed in the cases, when (1) an obstacle is inserted into the jet, and at the same time (2) a scale of a recirculation area ("bubble of separated flow") behind the obstacle is comparable with the nozzle-to-wall spacing. Annular impinging jet was studied numerically by Kokoshima et al. (1991), and a bistable behavior was predicted including a hysteretic character. The phenomenon was confirmed experimentally (for a planar geometry) by Trávníček and Křížek (1999) – the paper is probably the first publication on the bistability and hysteresis of impinging jets in a reviewed journal at all.

Recent study by Tesař (2001) presents an annular jet, when five flow regimes were identified (including bistability). Another example of an annular impinging jet is the Radial Jet Reattachment (RJR) nozzle (Page et al.,1989; Narayanan et al., 1998). The RJR nozzle is an annular nozzle with a predominantly radial orientation of an exit slot. The jet impingement (related with enhanced heat/mass transfer) is spread over a large surface area, and the pressure forces are efficiently controlled there. It is desirable for a manipulation of sheet materials by using the so called "bearing effect" of air jets (e.g., drying of both sides coated materials, when mechanical contacts with a sensitive wet surface have to be eliminated). It is worth mentioning that a typical nominal nozzle–to–wall spacing of the RJR is relatively small, thus the RJR works very far from any bistability.

The present paper is focused on a submerged impinging air jet from a two-slot nozzle. The nozzle has been designed as a slot nozzle, which is halved by a partition bar. The nozzle generates a two-dimensional air impinging jet, which is intrinsically bistable and hysteretic in character. Previous variant of geometry has been investigated by Trávníček and Křížek (1999), when the bistability and hysteretic behavior were confirmed by a measurement of the wall pressure, nozzle pressure drop, and local mass transfer coefficient. Recently, the bistability phenomenon was analyzed by Maršík et al. (2001).

Contrary to previous variants of a nozzle geometry (Maršík et al., 2001), the present nozzle is equipped with a wider and chamfered partition bar, and velocity vectors of jets issuing from the both half-nozzles are side–tilted, as plotted schematically on Fig. 1. A motivation of this design is to augment a nozzle–to–wall spacing, where a bistable behavior occurs.

3. Investigations

The smoke–wire technique (Corke et al., 1977) was used for the visualization of air flows. Smoke–wire (SW) was uniformly twisted from three resistance wires with 0.1 mm in diameter, and located across investigated jet flow. The SW was coated with paraffin oil before each test, and heated by the Joule effect of direct current. A continual bulb light or a flashlight were used and time-mean flow field pattern (pathlines) or instantaneous pattern (streaklines) were photographed, respectively. Pictures were taken by the digital camera (Olympus C–2500L Camedia).

Figures 1a, b show smoke visualization of both mean flow field patterns (pathlines), which were generated under the same conditions. Air flow is supplied by a centrifugal blower, air flow rate is controlled by a frequency regulator, and measured by a plate orifice located upstream the nozzle. The mean velocity at the jet exit is calculated from the airflow rate, $\upsilon_{AV} = 10$ m/s, widths of both "half-nozzles" are $b/2 = 5.0$ mm, nozzle–to–wall spacing is $s = 8.5\,b$. The Reynolds number is calculated as the $Re_{AV} = \upsilon_{AV} b/\nu = 6030$.

The both patterns (Fig.1 a, b) differ in a "bubble of separated flow", either a small or large recirculation area is embraced inside the jet. Fig. 1a shows A- flow field pattern: *Small recirculation area* is localized behind a central partition bar of the nozzle, stagnation flow is approximately similar in character with a basic case of a slot impinging jet (at least at the wall). Fig. 1b shows B- flow field pattern, which is quite different: *Large recirculation area* bridges the whole nozzle-to-wall spacing.

Figures 1c, d show an identical situation as Figures 1a, b, i.e., A– and B– flow field patterns, respectively. Figures 1a, b show a time-mean flow field, Figures 1c, d show instantaneous pattern (streaklines). Trains of vortices in jet shear layers are clearly visible on Figures 1c, d. An additional observation of the vortices was performed under a stroboscope light, an airflow rate was decreased for this observation (υ_{AV} = 2.5 m/s, Re_{AV} = 1600). The vortex passing frequency was evaluated as 155.8 Hz. The Strouhal number was calculated from the half-with of the nozzle ($b/2$ = 5mm), and it equals St = 0.31.

Figures 2 a, b show a typical heat/mass transfer behavior on the exposed wall at the A– and B– state of flow, respectively. (For a good comparison, the length scales are the same in Figures 1 and 2.) Mass transfer experiments were made by using naphthalene sublimation method (Goldstein and Cho, 1995), and a distribution of the non-dimensional local mass transfer coefficient is plotted on Figures 2 a, b. Sherwood number is defined as $Sh(x) = \beta(x)\, b / D_C$, where $\beta(x)$ is local mass transfer coefficient, and D_C is the diffusion coefficient. Fig. 2a demonstrates clearly that A– jet flow situation on the wall is approximately similar to a basic one-slot impinging jet. On the other hand, B– jet flow with *large recirculation area* is spread onto the wall (Fig. 2b). Two stagnation points are located on the both sides, they are associated with two side–maxima of heat/mass transfer. A reverse stagnation point is located on the geometry axis instead of standard one, it causes only small (however clearly visible) central local maximum of heat/mass transfer.

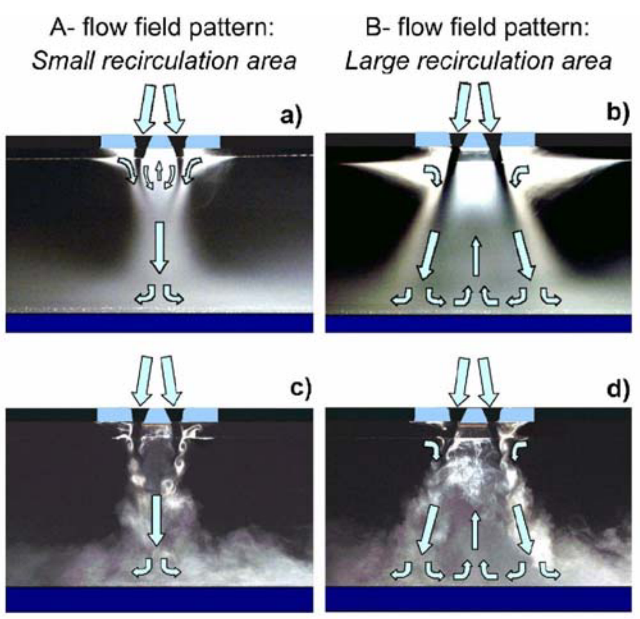

Fig.1 Bistable two-slot impinging jet, b = twice 5mm =10mm, $s = 8.5\,b$, $Re_{AV} = \upsilon_{AV} b/\nu$ = 6030, (υ_{AV} = 10 m/s). a, b ... time-mean flow patterns (pathlines) in a continual light, 1 s exposition; c, d ... instantaneous flow pattern (streaklines) in a flashlight.

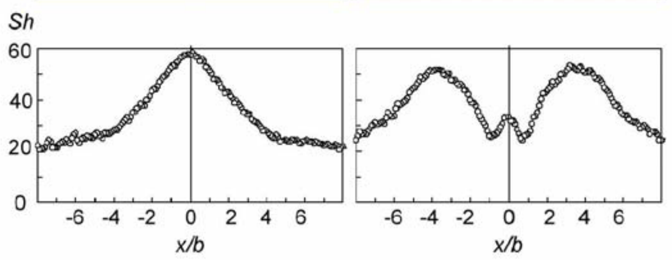

Fig. 2. Local mass transfer coefficient, $s = 8.5\,b$, Re_{AV} = 5500, (υ_{AV} = 8,5 m/s). the length scales are the same in Figures 1 and 2.

Fig. 3 shows large region of nozzle-to-wall spacing, where the bistability occur. In fact, the both flow field patterns can be identified by measurement of the wall pressure, nozzle pressure drop, and local mass transfer coefficient (Trávníček and Křížek, 1999). Fig. 3 shows a nozzle pressure drop in a non-dimensional form of the Euler number, $Eu = \Delta p/q$, where $\Delta p = p_{0in} - p_b$ is a pressure difference between a total pressure measured upstream the nozzle (p_{0in}) and the barometric pressure (p_b); the $q = \rho\, \upsilon_{AV}^2/ 2$. Large recirculation area of the B- flow pattern is associated with bigger circulatory mass flow, and bigger momentum flux. Therefore the dissipation of B- flow pattern is bigger, and *Eu* number is higher (Maršík et al., 2001). The arrows indicate sudden changes (switching) of the flow pattern, which occur, if the nozzle–to–wall spacing is gradually (step by step) changed. It is worthy to note here a very large range of the bistability, $s = 6.5\, b$ to $10.0\, b$.

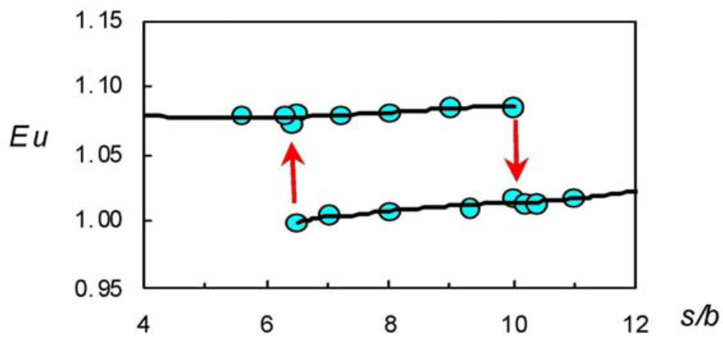

Fig. 3. Hysteretic behavior of the flow field presented by the nozzle pressure drop. The $Eu = \Delta p/q$, where the $\Delta p = p_{0in} - p_b$ is a pressure difference between a total pressure measured upstream the nozzle (p_{0in}) and the barometric pressure (p_b); $q = \rho\, \upsilon_{AV}^2/2$; s/b is the dimensionless nozzle–to–wall spacing.

4. Conclusions

The bistability and hysteretic behavior of submerged impinging air jet from a two-slot nozzle has been experimentally confirmed. Smoke visualization, measurement of some characteristics of the mean flow, and mass transfer experiments were performed. Two flow field patterns exist under the same boundary conditions, they differ in the recirculation areas of the "bubble of separated flow". Either s*mall* or *large recirculation area* is embraced inside the jet:

- In the former case, the s*mall recirculation area* is localized behind the nozzle partition bar only, and the stagnation flow on the opposite wall is approximately similar in character with a basic case of a slot impinging jet.
- In the latter case, the *large recirculation area* bridges the whole nozzle-to-wall spacing. Two stagnation points are located on the both sides; they are associated with two side-maxima of heat/mass transfer. Reverse stagnation point is located on the geometry axis instead of standard one, it causes a weak central local maximum of heat/mass transfer.

Modeling of bistability is considered important from a fundamental point of view in fluid mechanics as well as thermodynamics. Moreover, it is believed that the present investigation of bistability problems shall allow a further growth of various applications based on advanced impinging jets in the near future. The better understanding of the above phenomena get us moreover a possibility of an effective control of heat/mass transfer in these applications. First of all, the case of the *large recirculation area* submerged inside an impinging jet seems to be very promising for a desirable augmentation of heat/mass transfer.

Acknowledgments

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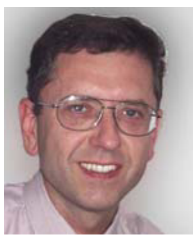
Authors Profiles



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