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Experimental study of gas entrainment from surface swirl

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ABSTRACT

Gas entrainment from surface swirls is characterized using water experiments. A free surface shear flow is generated in an open channel flow. A suction nozzle is set at the bottom of the test section to induce a downward flow and provoke gas entrainment. An important originality of these experiments is the possibility to change the inlet condition so as to generate different turbulent shear flows. This is done by adding obstacles of different sizes and shapes at the end of a flat plate separating the inlet flow from a "stagnant" water area. Velocity fields and profiles, measured with the PIV technique, are provided both to describe the inlet conditions corresponding to various geometries and flow rates, and to characterize the temporal average shear flow generated within the centre part of the channel. Gas entrainment mappings are established from direct observations of the different flow configurations. These new results show that the threshold for the suction velocities required to entrain gas are similar for the configurations with small obstacles and the flat plate configuration triggering a standard shear flow. Increasing the size of the obstacles promotes gas entrainment and reduces the threshold values of the suction velocity to trigger gas entrainment. Shadowgraphy with image processing is used to present new results characterizing the geometrical properties of surface swirls and the quantity of gas entrained. Inlet configurations with obstacles generate larger surface swirls which move upstream from the suction nozzle centre whereas they are situated downstream with the flat plate configuration. Moreover, dimensionless power laws are found to be good approximations for the surface swirl width and the quantity of gas entrained. In addition to provide new insights about gas entrainment in analytical configurations relevant to Sodium cooled fast nuclear reactor, these results should provide different test cases for the validation of MCFD codes.

Contents

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1. Introduction

Gas entrainment has been identified as a possible safety issue in Sodium cooled fast reactors (NaSFR). Gas captured from the free surface can be transferred to the bottom of the vessel. This may lead to the accumulation of gas pockets under the core of the reactor (Takahashi et al., 1988; Tenchine, 2010; Tenchine et al., 2014). When these gas pockets get through the core, they can disturb the nuclear reaction and damage the combustible rods. This gas entrainment phenomenon is produced by the combination of existing turbulent structures close to the free surface, such as eddies, and the downward flows created by the suction of hot liquid sodium by the intermediate heat exchangers.

Many experimental facilities have been designed to investigate this phenomenon in relation to the nuclear application. Most of them are water experiments and a brief history can be given.

Baum and Cook (1975) study the problem through a cylindrical glass apparatus. Here the eddy structure is generated by introducing the flow with a tangential inlet pipe. The liquid exits through an outlet pipe at the centre of the bottom of the cavity. Four liquids were investigated: water, white spirit, Freon 113 and sodium. They determinate the onset of gas entrainment for the four liquids.

Flow mechanisms of air entrainment were also studied by Takahashi et al. (1988) through an experimental set up close to that used by Baum and Cook (1975). The novelty of their rig and experiments is the possibility to add a forced circulation by turning the cylindrical cavity. In particular, they showed that an air core with break up bubbles changes to a continuous air core with an additional forced circulation.

In these experimental investigations, the gas entrainment is maintained continuously whereas it appears intermittently in NaSFR. Moreover, Kimura et al. (2008) have performed experiments in a partial model of the Japan Sodium cooled Fast Reactor[1] to show that gas entrainment results from the combination of the wake of obstacles, the presence of shear flows and the suction flow.

Then, to study intermittent gas entrainment, new analytical experimental facilities have been designed so as to isolate the key mechanism of turbulent shear flows combined with flow suction, *e.g.*, Kimura et al. (2009) and Cristofano et al. (2014). These new design experiments are based on open channel flows. To produce turbulent structures, a shear flow is generated in the middle of the channel. This is realized by separating the main flow from a water dead zone using vertical plates at the inlet and outlet of the channel. The downward flow is generated by flow suction through a nozzle placed at the bottom in the centre of the channel. This combination can produce (or not) gas entrainment through the suction nozzle according to the chosen flow parameters. Such experiments provide the occurrence map of gas entrainment according to flow parameters, *i.e.* inlet velocity, outlet velocity and suction velocity. Moreover, Kimura et al. (2009) have investigated both sodium and water fluids using the same test section to demonstrate that water experiments simulated well the onset conditions of gas entrainment in sodium.

Gas entrainment experiments have also been performed in liquid metal, *e.g.* Vogt et al. (2015, 2013) to support the validation of numerical codes.

It is worth mentioning that gas entrainment is also a topic relevant to the automobile industry in the context of the water box (Recoquillon et al., 2011b, 2011a; Recoquillon, 2013).

The present study is an experimental investigation of the gas entrainment occurrence in water. The geometry of the experimental channel is close to that of Ezure et al. (2008) and Kimura et al. (2009). The main difference lies in the inlet conditions. To trigger different flow regimes, obstacles of various shapes are added (or not) at the end of the flat plate defining the inlet conditions.

The experimental set up and methods are described in Section 2. The results are discussed in Section 3. New results about gas entrainment are presented for the different inlet conditions. First, the required condition on the inlet and suction velocities for the occurrence of gas entrainment are studied and compared to previous literature. Second, the geometrical properties of surface swirls are characterized. Third, the projected areas of the air pumped via bubbles entrained through the suction nozzle are measured. This permits to describe and compare the behaviour of surface swirls and the quantity of air entrained according to different inlet configurations.

[1] Their choice of the 1/1.8 scale was based on the works of Eguchi et al. (1994) and Eguchi and Tanaka (1994).

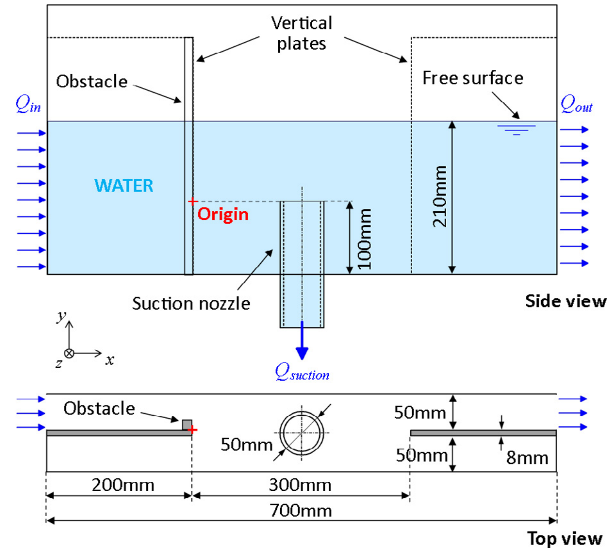

Fig. 1. Test section of the rig BANGA. The top picture is the side view and the bottom one is the top view. The origin of the Cartesian frame is indicated with a cross. Q_{in} and Q_{out} denote the inlet and outlet flow rates, respectively.

2. Experimental approach

2.1. Experimental setup

Experiments are performed using an open channel water flow. This channel is integrated in a closed loop. A centrifugal pump mounted with an adjustable by-pass is used to generate different regulated flow rates. Flow rates are measured by electromagnetic flowmeters with an accuracy of ±0.3%. Moreover, the temperature of the water is regulated at about 20 °C using a heat exchanger.

The length and width of the test section are respectively 700 mm and 108 mm. The height of the free surface is 210 mm. Fig. 1 gives a sketch of the test section of the rig which is named BANGA.

To separate the main free surface flow from a stagnant water area, two vertical plates (300 mm apart) are placed in the middle of the channel so that inlet and outlet flows are limited to the half of the channel cross-section. To induce a secondary down-flow, some water is pumped through a suction nozzle. The diameter of the nozzle, noted *D*, is of 50 mm and it is set at 100 mm height, *i.e.* 110 mm below the free surface. The origin of the Cartesian frame is set on the border of the vertical plate at the height of the suction nozzle. The *x* axis coincides with the horizontal channel flow direction, *y* and *z* axis are the horizontal and vertical directions, respectively.

The present experimental set up is relatively close to that of Ezure et al. (2008) and Kimura et al. (2009). One of originality of