Experimental investigation of free surface vortices and definition of gas entrainment occurrence maps

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Abstract. For the future development of Generation IV nuclear reactors, both safety and economic targets have to be achieved. In order to increase, at the same time, the power density generation and the safety features, a huge R&D effort is still required. Referring especially to Liquid Metal Cooled Fast Reactors, much attention is placed on Gas Entrainment (GE) phenomena, which could cause unlikely positive reactivity insertion accident. The GETS experimental facility (Gas Entrainment Test Section), especially aimed at studying the free surface vortices occurrence, has been built in the thermal-hydraulics laboratory of the DIAEE. The main purpose of this facility is to identify the most important parameters affecting the whirlpools formation and evolution. Experimental tests and preliminary observations have been performed. Different vortex behaviours related to different experimental conditions have been identified and presented in the present paper. 2D occurrence maps as function of different dimensionless groups (Reynolds, Froude and Weber numbers and $H^* = H/d$ ratio) have been defined. In the present paper, the results of a first experimental campaign, carried out with tap water, are discussed.

1. Introduction

The free surface vortices occurrence is an important issue in many hydraulic intakes (i.e. pumps and turbines) since strong free surface vortices introduce swirl flow at the intake causing entrainment of floating matters and gas (air or other gases). These conditions are considered more or less harmful for both the intake itself and the downstream devices. The free surface vortices formation has been studied in the last fifty years due to the important issues related to this phenomenon. In the hydraulic field, many studies have been performed to prevent the free surface vortex formation while, only in the last years, the GE phenomenon was considered an important issue in the nuclear industry. The GE, due to free surface vortex formation, can strongly affect the reactor safety performance especially in liquid metal cooled reactors. A volume of slightly pressurized inert gas is always maintained above the liquid metal free surface in order to avoid chemical reaction issues both due to the liquid metal or to the air. On the other hand, the presence of the inert gas, above the free surface, can cause gas bubbles entrainment into the primary coolant. Because of the GEN IV nuclear reactors have to be economically competitive with LWRs, it was necessary to foresee a reactor vessel size reduction, an increase in the reactor density power and hence in the coolant velocity within the primary circuit. This means increasing in the upper plenum coolant velocity causing instability in the free surface and
enhancing the risk of free surface vortex formation as well as other GE phenomena occurrence, if any special solution will not be foreseen (e.g. vortex breaker). The presence of any gas bubble entrained into the reactor coolant, and hence the passage through the reactor core, can affect the reactor safety leading to abnormal conditions up to accidents. In particular, GE occurrence can cause:

- reactor instability (i.e. reactivity fluctuation);
- thermal crisis due to sudden reduction of the local heat transfer coefficient;
- thermal stresses, especially to those structures in contact with both liquid metal and cover gas;
- cover gas activation, which can reduce the safety system performance;
- increasing in the instrumentation noise.

Due to these important safety issues, the free surface vortex phenomenon has to be deeply investigated, in order to understand the formation mechanism and to prevent the occurrence. Because of its own physical structure (e.g. gas-liquid interface, instability, etc.), the free surface vortex phenomenon results to be very difficult to study and its dynamics is not yet well understood.

Several paths have been followed to study the free vortex formation and evolution, and they can be grouped in analytical, numerical and experimental approaches, respectively: definition of the velocity fields from the Navier-Stokes equations, CFD simulations and development of empirical correlations. The first theoretical vortex model, aimed at defining the tangential flow velocity, was proposed in the mid ‘800 by Rankine [1]. Following this first approach, the work of Burgers [2] was focused at the solution of the Navier-Stokes equations, considering the axial velocity linearly dependent from the axial position. The first complex models, based on experimental observations, were proposed by Chen et al. [3]. Odgaard [4] proposed correlations to calculate the depth of incipient air entrainment critical submergence and investigated on the most important factors affecting the phenomenon. A more consistent theory, focused on vortices within a rotating vessel, was proposed by Lundgren [5] and Andersen et al. [6] added later the effects of the surface tension and of the viscosity in the Ekman boundary layer near the outlet orifice. Later, Stepanyants et al. [7] extended this model to a non-rotating vessel. An analytical expression of the free surface vortex velocity was derived by Hite et al. [8]. Several dimensional analyses and experimental tests, aimed at identifying dimensionless groups able to describe the phenomenon, were performed by many researcher groups [8]-[13]. In order to make the phenomenon more stable during the time, a special geometrical configuration (i.e. imposition of a tangential inlet) was selected by Moriya [14] and Monji et al. [15] to study the velocity distribution around the vortex. Some experimental tests were carried out by Kimura et al. [16]-[18] to study the free vortex occurrence under specific conditions (e.g. in the Japanese Sodium Fast Reactor - JSFR): the authors developed a scaled down partial model of the JSFR to understand the main factors and mechanisms related to the GE within this geometry. This scaled model was aimed at investigating how the fluid physical properties affect the GE phenomena, and to evaluate the size distribution of entrained bubbles from free surface vortices. Some studies based on the numerical approach, especially those of Sakai et al. [19] and Ito et al. [20]-[21], were focused on the development of a high precision methodology based on Volume Of Fluid – VOF - algorithm to be used in numerical simulations. The above mentioned most important research works guaranteed steps forward in the understanding of vortices formation but the free surface vortex formation and its evolution mechanisms are not yet well understood.

In this work experimental tests, carried out to analyse the vortex formation and the GE phenomena, and their occurrence maps based on qualitative observations of the vortex, are presented. Dimensionless groups have been investigated to evaluate the influence of the outlet tube diameter, surface level and flow rate.

2. Experiments

To carry out the experimental tests, the GETS facility (Gas Entrainment Test Section), with water at the ambient temperature as working fluid, was used. The experimental facility includes a
parallelepiped-shaped tank (made of PMMA), a circulation pump, valves and a flow meter. It was designed and built mainly to study the GE phenomena, due to the free surface vortex, in a no vortices promoting geometry (figure 1). In order to investigate how the drain diameter affects the GE phenomenon, a special flanged connection has been studied; it allows to easily change the diameter of the draining pipe without any other changes in the facility layout. Moreover, the most important parameters that can be changed are the mass flow rate and the free surface level. From this experimental campaign, different occurrence maps, focused on the GE onset condition, have been obtained.

2.1. Experimental setup

In figure 1 a flow diagram and a 3D view of the GETS facility are shown. The facility is realized to allow an easy filling and draining of the tank, to control finely the mass flow rate and to change the inlet flow configuration (i.e. passing from two symmetrical inlet flows up to an asymmetrical inlet). To perform experimental tests both in steady state and transient conditions (blow-down) the GETS facility can operate as a closed or open loop.

The draining and refilling operations are carried out by an auxiliary line, which is connected through a shut-off valve to the pump upstream line. The water flow rate can be controlled both by the regulation valve (coarse regulation) and by the inverter installed on the pump motor (fine regulation). Concerning the inlet flow condition, the steady state with symmetrical inlets (valves fully opened) has been considered in the present work.

![Figure 1. A schematic and a 3D views of the GETS test section](image)

The GETS layout foresees that water is drawn from the tank through the circular orifice to the draining pipe up to reaching the circulating pump. Downstream the circulating pump, a flow meter with its upstream and downstream free lengths, to avoid any effect on the flow rate measurements, is foreseen. A vortex flowmeter, Prowirl 73F produced by Endress-Hauser, has been used to measure flow rates from 85 l/h to 3400 l/h with an accuracy of 0.75% of the measured value.

Before reaching the tank again, the flow passes through the regulating valve and, after a tee joint, it reaches the two shutoff valves upstream the two inlet nozzles. Finally, the flow, through two completely symmetrical inlets, enters the active volume of the tank (external dimensions 700 mm × 500 mm × 500 mm - height×length×width - with walls 20 mm thick), where the free surface vortex observations can be performed. In order to overcome the constraints of a free surface vortex induced by the facility geometry, as in the most of the previous research works, the GETS facility has been designed to allow completely symmetrical inlet flows, which do not generate a rotating flow within the tank. In order to avoid (or limit) any free surface perturbation, vertical baffles are foreseen between the inlet and outlet nozzles. Thanks to these baffles, the upward inlet flows can reach horizontally the
active zone of the tank, near the outlet orifice, limiting the free surface perturbations to the lateral zones (not included in the active volume of the tank).

The outlet orifice, in the centre of the tank bottom wall, has been equipped with three different draining pipes (i.e. \( d = 14 \text{ mm}, 26 \text{ mm} \) and \( 38 \text{ mm} \) inner diameter) thanks to the flanged connecting system; the connection flange has a diameter of 100 mm with four screws to assure a fixed position. The connected draining pipe is also made of PMMA in order to make easier the observation of the outlet flow for several diameter under the tank.

In figure 2 the GETS facility, during current experiments aimed at measuring the velocity fields by the PIV (Particle Image Velocimetry) technique, is shown.

![Figure 2. GETS facility during PIV measurements](image)

2.2. Experimental procedure

The present study is focused on the development of occurrence maps, based on qualitative classification criteria, aimed at defining the onset condition for GE under different operating conditions. To obtain comparable observations, the following specific procedure has been developed and followed during the experimental tests:

- **initial condition:** from the previous test, tank filling or level changing;
- **waiting period:** a waiting time of 10 minutes is required to reduce free surface oscillations and to prevent vortex induction from the starting transient, until a steady condition within the tank is reached (the coarse regulation of the pump flow rate is performed before this waiting period);
- **fine regulation:** by means of the regulating valve and the pump inverter, the fine regulation of the flow rate can be completed;
- **observation:** the tank active zone is observed for a period of 10 minutes, recording the mass flow rate, the temperature (to evaluate correct values of the thermodynamic water properties) and the flow qualitative condition (see Table 1);
- **conclusion:** after 10 minutes of observation, the regulating valve and the free surface level are regulated for the next test.

Overall, each test lasted 1200 seconds. This procedure allows to compare data from different experimental tests preventing any possibility of vortex induction by the initial flow condition. The qualitative observation criteria, used in the present work, is derived from Hecker’s [22] method and it is shown in Table 1.
### Table 1. Qualitative classification criteria

| Stage | Name                           | Description                                                                 |
|-------|--------------------------------|-----------------------------------------------------------------------------|
| 1     | Surface swirl and very small   | A constant visible swirl and a very small deformation on the free surface.  |
|       | dimple                         | Curvature observable only by means of the refraction phenomenon.             |
| 2     | Well-developed dimple          | A deformation of at least a few millimetres in the centre of the swirl.     |
| 3     | Bubble entraining core         | Vortex pulls air bubbles into the intake.                                   |
| 4     | Full air core                  | Vortex pulls constant stream of air into the intake.                        |

### 2.3. Experimental conditions

The experimental tests have been performed with a quite wide range of the main parameters affecting the free surface vortex phenomenon. The minimum and maximum values of the main parameters are shown in Table 2.

#### Table 2. Main parameter ranges.

| Parameter                | Minimum value | Maximum value |
|--------------------------|---------------|---------------|
| Pipe inner diameter [mm] | 14            | 38            |
| Mass flow rate [kg/s]    | 0.025         | 0.625         |
| Free surface level [mm]  | 50            | 225           |

In this study, the following dimensionless groups have been considered:

- the Reynolds number \( Re = \frac{\rho(T)Ud}{\mu(T)} \)
- the Froude number \( Fr = \frac{U}{\sqrt{gH}} \)
- the Weber number \( We = \frac{\rho(T)U^2d}{\sigma(T)} \)
- the dimensionless depth \( H^* = \frac{H}{d} \)

where \( d \) is the inner diameter of the pipe, m; \( g \), gravity acceleration, 9.806 m s\(^{-2}\); \( H \), water level, m; \( T \), water temperature, K; \( U \), average outlet velocity, m s\(^{-1}\); \( \mu \), dynamic viscosity, Pa s; \( \rho \), water density, kg m\(^{-3}\); \( \sigma \), gas-liquid surface tension, N m\(^{-1}\). Water temperature varied from 18.6º C to 32.5 ºC. In this range, the water density and dynamic viscosity varied, respectively, from 998.48 to 994.9 kg/m\(^3\), and from 1036.92 to 758.26 μPa∙s, Surface tension varied from 0.07295 to 0.07082 N/m. Reference has been made to IAPWS- 95 (Int. Ass. for the Properties of Water and Steam, Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use).

### 3. Results and discussion

#### 3.1. Experimental observations

During the experimental tests all the four vortex stages have been observed and occurrence maps have been generated merging experimental data obtained with the different outlet tube diameters. A not
perfectly stable condition has been identified in all the performed tests. The vortex position moved during the time, driven by the instantaneous conditions of the flow. Moreover, the vortices strength changed during the tests, resulting in a continuous variation of the vortex depth. It is not clear if this instability is a peculiar characteristic of the physical phenomenon, or if it only caused by the tank geometry and flow perturbations introduced by the pump. Anyway, each experimental condition has been classified considering the worst vortex stage observed during the test.

Figure 3. Pictures of vortex different stages: a) Stage 1, b) Stage 2, c) Stage 3, d) Stage 4.

Figure 4 shows the four different stages considered in this analysis. Mirror images visible in the pictures are due to the reflection of vortex on the water free surface. This effect can’t be avoided due to the position of the camera below the free level surface.

The vortex Stage 1 (figure 4-a), which is the initial stage for the formation of a vortex, is characterized by a constant swirl and a very small deformation of the free surface, which can be only observed through the light refraction. Thanks to tracer particles, it has been observed that, even in this stage, the rotational flow is not confined only to the free surface but it affects the entire zone near the outlet orifice.

The Stage 2 includes all vortices that have an appreciable free surface deformation (more than 1 mm). As can be seen in figure 4-b, in this stage the vortex acquires an axial dimension and a gaseous core extends toward the outlet orifice; in this stage there is not bubbles detachment from the tip. As the vortex depth increases, the tip becomes thinner, and the surface tension has a greater importance in the shape definition of the free surface. When the depression of the gas-liquid interface is small the flow in the vortex core can be considered axi-symmetric while, when the vortex is well-developed, this is not true anymore. In these cases, the axis of the vortex is inclined because of the local conditions of the flow; probably because well-developed vortices occur at higher velocities and their thin structure is more sensitive to flow disturbances.

The Stage 3 is reached when, from the vortex, some bubbles are pinched off from the tip by the downward flow and are dragged into the outlet orifice (figure 4-c); this stage, therefore, involves a gas entrainment into the experimental loop, and it is particularly unstable, rapidly evolving to a worst condition (Stage 4) or comes back to Stage 2. Figure 4-c shows that the size of the entrained bubbles is comparable with the thickness of the tip of the gas core.

The Stage 4 conditions correspond to a full developed vortex whose tip reaches the outlet orifice (figure 4-d) causing a continuous gas entrainment into the experimental loop. When too much air is entrained, pump cavitation occurs and the flow rate goes down; thereby, the downward flow decreases and the vortex goes back to the Stage 2, passing through the unstable Stage 3. When no more air is entrained, the pump recovers its efficiency and the flow rate returns to the previous level, recreating the occurrence conditions for Stage 4 vortices.

Empirical correlations of the different transition zone boundaries have been obtained in [23], to reformulate the transition criteria in a dimensionless form.
3.2. Occurrence maps

The experimental results have been used to build 2D occurrence maps. In each map, the Stage 3 and the Stage 4 cases are gathered together in a single group (GE), because both conditions lead to gas entrainment phenomena. An evaluation of the different vortex stage zone boundaries has been done in the different occurrence maps; however, this must be considered only a preliminary and rough estimation of the transition boundaries, because of the qualitative classification criteria adopted in this work. The figure 5 shows the $H^*-Re$ occurrence map of the experimental tests carried out with the smaller tube diameter ($d = 14$ mm). It can be seen that the No vortices-Stage 1 and Stage 1-Stage 2 transition zones are well defined, while the Stage 2-GE transition zone is characterized by some mismatches; this is probably due to the greater importance that other dimensionless groups ($Fr$ and $We$), that are not considered in this map, have on the physical dynamics of the gas entrainment phenomenon. Moreover, the high flow rate in some cases, which correspond to high $Re$ numbers, introduced oscillations of the free surface and tiny waves that seem to have an inhibitory effect on the vortex intensification and the gas entrainment occurrence.

![Figure 4. $H^*-Re$ Occurrence map ($d=14$ mm)](image)

Other two 2D occurrence maps have been drawn plotting the experimental data, obtained with the smaller outlet tube diameter, in $H^*-We$ (figure 6) and $H^*-Fr$ (figure 7) graphs. Even in these two maps, the transition zones are quite well defined, and the most evident mismatches are localized in correspondence of the Stage 2-GE transition. Moreover, while the boundaries of the $H^*-Re$ map have an almost linear trend, the functional dependence of $H^*$ from $Fr$ and $We$ is clearly non-linear.

![Figure 5. $H^*-We$ Occurrence map ($d=14$ mm)](image)
The occurrence maps of the experimental results obtained with the two other outlet pipe diameters have similar trends to those shown in figure 5, figure 6 and figure 7.

In figure 8 and figure 9 two overall occurrence maps, obtained merging together the experimental results obtained with the three outlet pipe diameters, are presented. The data series characterized by different outlet diameters are not in perfect agreement with each other, and this means that the parameter \( d \) has a non-negligible effect on the formation and evolution of free surface vortices. However, the transition boundaries of the different vortex stage zones have been preliminary identified. Concerning the \( H^*-Re \) map (figure 8) and the \( H^*-We \) map (figure 9), a general agreement of the experimental results can still be noticed, at least for trends of the different transition zones.

Otherwise, in the \( H^*-Fr \) map (gathering together all the experimental data) no vortex stage zone boundaries have been identified. In this case, the series of experimental data obtained with different outlet diameters do not match well together. This fact could be explained considering that the \( Fr \) number, as defined in this paper, does not explicitly depend on outlet pipe diameter, unlike the \( Re \) and \( We \) numbers. In any case, it is evident that, concerning the \( Fr \) number influence on vortex formation and GE occurrence, the outlet pipe diameter has non-negligible effects.
4. Conclusions

The GETS facility has been built with the aim of experimentally study the formation and evolution of free surface vortices and the GE occurrence, and a first experimental campaign has been carried out. The observed phenomena have been classified according to qualitative criteria, and different 2D occurrence maps have been obtained.

The occurrence maps, related to a single outlet pipe diameter, show transition zone boundaries quite well defined, with the main mismatches located at the Stage 2-GE transition zone. This probably means that the Stage 2-GE transition is influenced, in a non-negligible way, by all the dimensionless parameters, that cannot be considered together in 2D maps. Furthermore, strong perturbations of the free surface, introduced by the high flow rates that characterize this transition zone, could result in experimental anomalies.

Concerning the overall occurrence maps, instead, quite good accordance has been obtained with the $H^*-Re$ and $H^*-We$ maps, and preliminary transition zone boundaries have been identified. Otherwise, a poor agreement of the experimental results, obtained with different outlet pipe diameters, has been observed in the $H^*-Fr$ map.

The GETS experimental facility is very useful to study of free surface vortices since it allows to observe the physical phenomenon and to analyse the influence of different parameters on it. However, further quantitative studies are needed to have a better comprehension of the free surface vortex formation, with the aim of defining some empirical correlations. With this purpose, an experimental campaign is being carried out in order to characterize the vortex velocity fields by the PIV (Particle Image Velocimetry) technique. Furthermore it will be important to evaluate the behaviour of different fluids and to determinate the dominating phenomena in each stage [23].

5. References

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