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FliHy experimental facilities for studying open channel turbulent flows and heat transfer

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Abstract

The FliHy (Flibe Hydrodynamics) facility was constructed at UCLA to study open channel turbulent flow and heat transfer of low-thermal and -electrical conductivity fluids. At present, water is used as a stimulant fluid for molten salt, e.g. Flibe. A similarity analysis matched the dimensionless parameters in the experiment with those in the ARIES-RS First Wall design. Unlike previous studies of open channel flow, the goal of the present one is to study supercritical flow regimes ($Fr > 1$), in which the surface waves are amplified and heat transfer is enhanced due to surface renewal. The paper describes the facility and gives the results of measurements of the flow thickness and their analysis.

Keywords: APEX; Liquid wall; Turbulence; Ultrasound; Surface waves; Heat transfer

1. Introduction

The Flibe Hydrodynamics (FliHy) facility was recently established to study fundamental flow physics, to assist in enabling liquid wall technology and its application to reactor design. Early work on FliHy mostly focused on shaking down the facility, testing diagnostics, and obtaining proof of principles. In the first experiment, an inclined open channel flow was used to study surface waves, which are expected to be a major factor affecting the heat transfer.

The FliHy facility components and structures are designed to handle a range of working fluids, including water, KOH, and other chemicals (such as oil). These fluids exhibit a variety of molten salt behaviors, both magnetohydrodynamic and thermal. The system is capable of reaching many of the dimensional and nearly all of the dimensionless flow parameters of the CliFF liquid wall design [1], e.g. Re, Fr, and We. In the CliFF design, molten salt flows poloidally from a toroidal chamber's top to bottom, forming a liquid layer with a thickness of 2 cm and velocity of 10 m/s. The FliHy test matrix covers a range of flow parameters even wider than that to be used in CliFF, with a range of flows from 2 to 75 l/s, as well as different inclinations of the test section.

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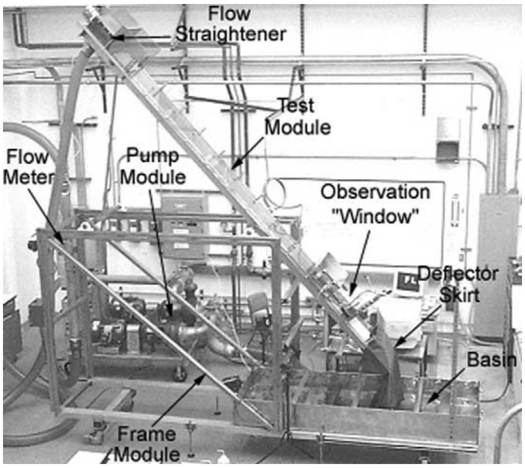

Fig. 1. Photograph of the FliHy facility with planar wall test section.

2. Experimental facilities

A photograph of the FliHy facility with the flat test section installed is shown in Fig. 1. The facility is divided into four main components:

1) The pump station is composed of two centrifugal pumps connected in parallel, capable of pumping 75 l/s of water at maximum speed. The pumps are individually controlled with variable speed inverters to allow variation of the flow rate.
2) The main frame is built of stainless steel and designed to accommodate test sections as long as 4 m. Unistruts at the top and sides allow the flexibility to position the test section at various locations and pivot the section to a wide range of angles. The lower section of the frame accommodates a large collection tank with a 1 m^3 capacity. A 6-inch discharge line at the bottom of the tank feeds the fluid to the pumps.
3) Built-in diagnostics tools include the flow meter, thermocouples, and IR heating equipment.
4) The test section module consists of a plane or curved open channel with an injection system and auxiliary support frames. FliHy can also accommodate closed-channel test sections.

2.1. Flat test section

The chute-type channel is designed to have a single-piece, smooth, planar bottom wall. The channel is capable of changing its inclination angle from the horizontal to vertical, to accommodate different orientation-dependant conditions and their respective flow rates. At the top of the channel is an injection system that includes a flow straightener and an adjustable nozzle. A stainless steel honeycomb is first used to reduce the turbulence from the inlet hose expansion. The flow passes through the honeycomb and encounters the nozzle, where it is reduced to the equilibrium height for the particular open channel flow run. The honeycomb provides a low level of the disturbances in the test section inlet, which is needed to avoid unwanted flow perturbations. The top piece of the nozzle is adjustable, such that different contraction ratios are possible. This precise exit-height control minimizes the transition length and also alleviates hydraulic jump phenomenon. Once exiting the nozzle with a thickness equal to or near the equilibrium one for a given inclination angle, the flow enters the open channel test module. The flow average height and velocity profile transition to a fully developed condition prior to encountering the observation ‘window.’ After passing through the window (and its associated diagnostics), the flow falls from the end of the chute via a deflector skirt into the frame basin.

All measurements, such as the flow thickness and surface temperature, are conducted over the flow region that is fully developed, which shows no variations of the mean flow thickness. To have such a flow regime, the observation ‘window’ (which measures 10×12 cm^2) is located approximately 3.5 m from the nozzle exit. Also, the nozzle height is adjusted in such a way to be as close to the equilibrium thickness as possible. This reduces the transition length significantly. This equilibrium flow thickness was predicted numerically using a ‘$k-\varepsilon$’ model [2]. Based on the calculations, the transition length due to the change in the velocity profile is considerably shorter than that due to the inlet height mismatch. If the inlet height is perfectly matched with the equilibrium thickness, the flow would require about 1 m to become fully

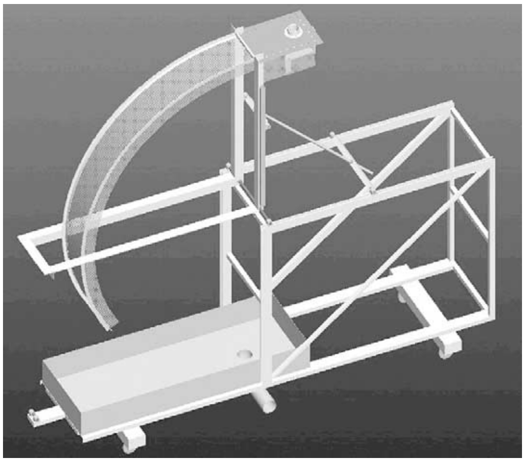

Fig. 2. Curved wall test section.

developed for almost all flow regimes. More generally, the length of the test section must be greater than this transition length due to both the velocity profile and the nozzle height mismatch effects. This length must also leave extra room for the observation window to view the behavior of the fully developed flow. In most experiments using the planar channel, all of these requirements were fulfilled through proper adjustment of the nozzle exit-height.

2.2. Curved test section

Unlike straight chute flows, flow over a curved wall experiences a gravity force that changes its magnitude and orientation with respect to the main flow over the entire flow length. This results in flows not becoming fully developed, regardless of the flow length. Such a situation occurs in the CliFF flow. The FliHy-implemented design shown schematically in Fig. 2 allows the rotation of the supportive frame along with the test section within a 180° arc to allow a wide range of configurations in order to simulate CliFF flows over the top, bottom and mid-plane sections. Further testing will incorporate specially designed flow obstacles to simulate the presence of wall penetrations. The main goal of these experiments is to study the flow behavior around penetrations and qualify design variations to insure proper flow coverage around them.

Table 1
Summary table of FliHy facility parameters

Parameter (units)	Capability range (flat module)	Capability range (curved module)
Volumetric flow rate (l/s)	3–75	10–75
Inlet velocity v (m/s)	0.15–9.0	4.8–9.4
Nozzle height (mm)	3–50	5–20
Inclination angle (°)	2–85	0–180
Heat flux (W/m^2)	$0–60 \times 10^3$	$0–60 \times 10^3$
Reynolds number, *Re*	$1 \times 10^4–3 \times 10^5$	$14 \times 10^3–1 \times 10^5$
Froude number, *Fr*	0.8–1500	70–3000

The curved 120° test section will be composed of a 1.9 m radius curved section, 4 m long, and 0.5 m wide, with 0.1 m high side walls. The minimum flow velocity that provides the flow adhesion in the most arduous (upside-down) case is 4.8 m/s. This is similar to the flat test section, in that almost all experiments will be performed in the supercritical range ($Fr > 1$), in which the surface is wavy and the surface perturbations are amplified. A fixed nozzle will span the full width of the test section to inject the flow tangentially and maintain a constant flow thickness. The initial nozzle design will have a 2 cm high flow opening. However, various low cost nozzles will be built with different opening sizes to vary the flow thickness and offer a wider range of flow parameters to be tested.

2.3. Summary of facility capabilities

Table 1 summarizes the FliHy facility capabilities and the most important flow parameters. The Reynolds number and the Froude number are given by $Re = vh/\nu$ and $Fr = v^2/gh$, respectively. Here, h is the fluid mean height, v is the bulk velocity, ν is the kinematic viscosity, and g is the acceleration due to gravity.

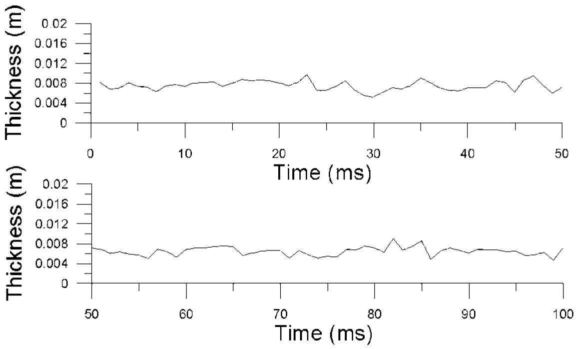

Fig. 3. Flow thickness data for 30° at 10 l/s.

2.4. Instrumental tools and techniques

Conducting measurements in the vicinity of the free surface or, moreover, directly at the surface is a great experimental challenge, especially if the interface is wavy. Free surface experimental techniques based on probes have many shortcomings and generally suffer from a lack of accuracy under wavy conditions. In contrast, the present instrumental tools are non-intrusive and include an ultrasound transducer for measuring the flow thickness and surface wave parameters, an infrared camera for diagnosing the surface temperature variations both in time and space, and a dye technique to enable flow visualization. To simulate the high surface heat fluxes encountered in the CliFF design, a 30×30 cm infrared heater is used to provide heating directly to the liquid from the side of the free surface. The heater is located just above the 'observation window' indicated in Fig. 1, where it facilitates the infrared camera diagnostic. Post analysis of this thermography is now underway. The data on the flow thickness variation obtained with the ultrasonic transducer and their analyses are given in Section 3.

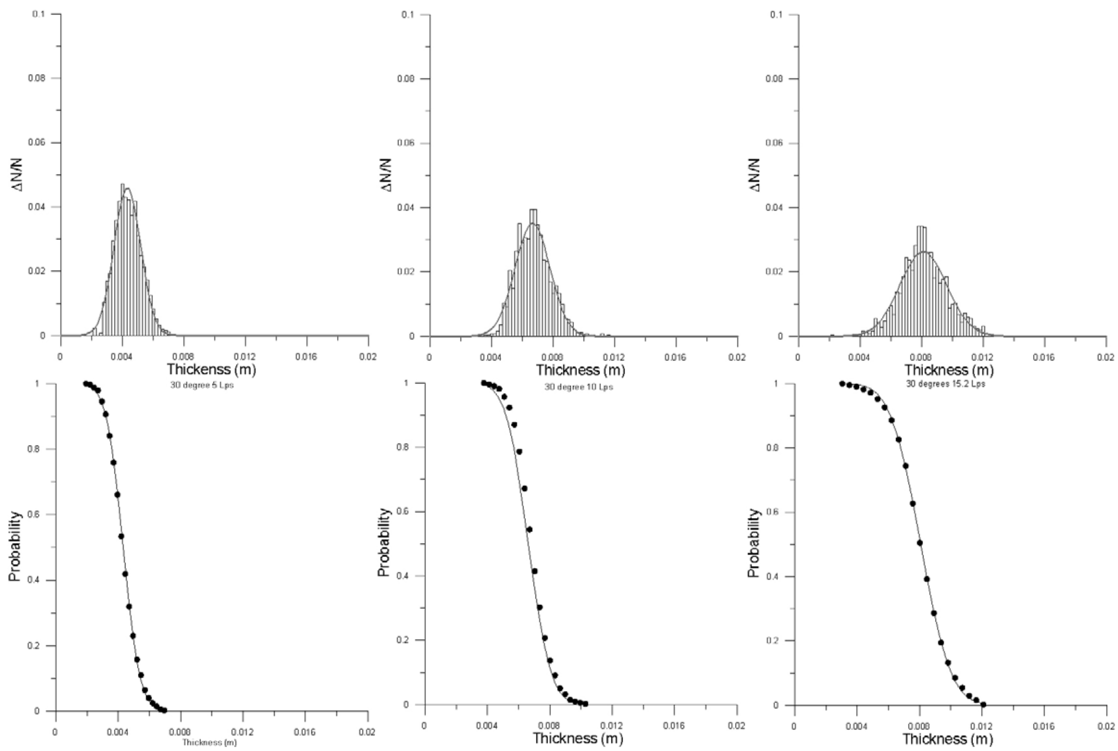

Fig. 4. Histogram, Gaussian distribution and cumulative probability function comparison for 30° inclination at 5, 10, and 15.2 l/s, respectively.

3. Ultrasound transducer and flow thickness measurements

In the first experimental set up of FliHy, a single transducer was mounted to the center back wall opposite to the observation window. This gives a measurement of the middle flow thickness as a function of time. The measurements of the flow thickness are based on the detection of the time interval between the two reflections of the ultrasonic echo: from the back wall–water interface and that from the free surface. All the reflections are visualized with an oscilloscope and recorded by a computer for further analysis. A special FORTRAN program, called the FUDA code, was written to evaluate the free surface turbulence statistics from the original data sets. Fig. 3 shows the initial results for 30° data, processed from a test matrix that includes inclination angles from 0.1 to 75° and flow rates from 4 to 20 l/s, corresponding to $1 \times 10^4 < Re < 5 \times 10^4$ and $0.9 < Fr < 1250$. As can be seen from the principle result shown in Fig. 4, the CliFF-like supercritical flows exhibit a gaussian profile, not a gamma profile as suggested by Chu and Dukler [3]. This is attributed to their flow being dominated by capillary effects and implies a continuous distribution for CliFF-like flow's power spectral densities versus frequency. No 'substrate and bulb' formation was observed. Additionally, one can observe from Fig. 4 a trend in the changes in the flow height and wave amplitude for a given angle, flow rate. As the latter increase, the flow tends to broaden and flatten its wave distributions. Overall, this means more white noise-type waviness, rather than the organized structures observed in Ref. [3].

4. Concluding remarks

The FliHy facility construction and shake down are complete. Initial experiments have been conducted and some preliminary analyses of their data were performed. The present paper gives a general description of the facility, the goals of the study, and explains details of the diagnostic instruments employed. It also discusses the techniques used for diagnosing the free surface phenomena, most notably for the ultrasonic data revealing an important surface-wave trend and contrast its results to previous work. Future studies will concentrate more on analyzing the phenomena themselves, especially in regards to thermographic comparative analysis to $k-\varepsilon$ modeling results. The first analysis that uses the current experimental data is presented in the present proceedings [4]. This includes further statistical treatment of the experimental data, comparisons with the numerical results based on the $k-\varepsilon$ model of turbulence.

Acknowledgements

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