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Adiabatic Air-Water Two Phase Flow Experimental Facilities Design, Construction and Operation

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Adiabatic Air-Water Two Phase Flow Experimental Facilities
Design, Construction and Operation

Thesis
Submitted in partial fulfillment of
the requirement for the degree
Master of Engineering (Mechanical)
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Approved:

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Abstract

Experimental studies are conducted to predict the phenomenon(s) and to describe some kind of causation. The design of experiment and the experimental facility is a rigorous method. A well designed, manufactured and operated experimental facility is robust under criticism.

Thermal hydraulic characteristics of air-water two-phase flows in a vertical tube (poly-dispersed) and also annulus (mono-dispersed) have been subjected to be studied in detail. The hydrodynamics modeling and simulations need a detailed comparison and verification with experimental results. Obviously, a well-designed experimental facility is required to provide a set of highly accurate and reliable data. To do so, two different research facilities have been designed, constructed and operated based on the relevant technical requirements and regulations to conduct the experimental researches.
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Nomenclature
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<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>$\dot{m}_G$</td>
<td>Gas Mass Flow Rate</td>
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<td>$\dot{m}_L$</td>
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<td>Nd:YAG</td>
<td>Neodymium-Ddoped Yttrium Aluminium Garne</td>
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<td>PFD</td>
<td>Process Flow Diagram</td>
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<td>PIV</td>
<td>Particle Image Velocimetry</td>
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<tr>
<td>t</td>
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<td>$V_{SG}$</td>
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<td>$V_{SL}$</td>
<td>Superficial Liquid Velocity</td>
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<td>Mass Quality or Dryness Fraction</td>
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**Subscript Nomenclature**
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<td>Superficial Liquid ...</td>
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Chapter 1
Introduction

The adiabatic two-phase air and water experimental facilities described in this report have been designed, manufactured and successfully operated creating a simultaneous flow of a gas (air) and a liquid (water). The aim is to provide an accurate and reliable flow field measurements and local hydrodynamic data by using the advanced PIV techniques. Thus, the corresponding empirical correlation and mathematical model within validation of their dynamics related models using CFD codes would be proposed.

The first apparatus described in section 3.1, is to generate a poly-dispersed bubbly flow in a vertical tube with an upward water flow. This experimental set-up involves a long vertical tube test section with an air-water upward bubbly flow and a sudden expansion in the middle of the column; in which the two flow conditions will allow us the investigation and analysis of the axial development of the bubbly flow up to the transition to slug and annular flows. Meanwhile, the local measurements of void fraction distribution, bubbles shape and size, interfacial area concentration, water and bubble mean axial velocity at different axial locations are also foreseeable. After a successful data acquisition, a validation of interfacial forces and area source and sink terms due to coalescence and break up, and the relevant turbulence models will also be considerable.

The second apparatus described in section 3.2, is to generate a mono-dispersed bubbly flow in an annulus with an upward flow of water. This experimental set-up involves a vertical annulus test section injecting air bubbles into the gap between the inner and outer tubes; in which the two flow conditions will allow us the investigation of the sub-cooled flow boiling and study the dynamics of bubble generation and measurements of the bubble growth, sliding distance, mean diameter, mean axial velocity, deformations, void fraction distribution to obtain a sufficient reliable set of data for the validation and 3-D reconstruction and CFD simulations.

This master's thesis report includes the theory and background of the air-water two-phase flow, and mainly discusses the design, manufacturing and operation of the two above mentioned experimental facilities to be used in the relevant research projects.
Chapter 2

Theory and background

A simultaneous motion of the air and water inside a vertical tube is a two-phase flow that can be upward or downward in which the conditions of the flow can change in different axial locations, with time and geometry of the column that can result the development of different flow patterns or flow regimes along the tube. The change of the conditions and interface configurations in the air-water flow is mostly due to the deformable nature of gas-liquid interfaces. Two deterministic parameters in the development of the flow regimes in the air-water two phase flow are the interfacial tension forces which separate the phases, and the exchange of momentum between the air bubbles and water in the flow.

Several different flow patterns in the upward air-water flow in a vertical tube could be observed (Fig. 1). The distinctive main flow patterns are: bubbly, slug/plug, churn, froth, and annular. These flow regimes can be described in terms of "mass quality" and "superficial phase velocity". The term of "mass quality" or "dryness fraction" is expressed as the ratio of the gas flow rate to the total (gas-liquid) flow rate:

\[ x = \frac{\dot{m}_G}{\dot{m}_G + \dot{m}_L} \]

The term of "superficial phase velocity" is the velocity that each phase of the gas or liquid could have if it flowed alone in the tube.

The different flow patterns are described as follows:

**Bubbly flow**: The most widely known flow regime that the gas phase (air) is distributed in discrete bubbles of approximately uniform size within a liquid (water) continuum.
**Slug/Plug flow**: By increasing the superficial gas velocity, the number and sizes of the bubbles will increase; meanwhile the coalescence of the larger bubbles can create the large bullet-shaped bubbles into the water flow, so called slug flow. Some small air bubbles still available and distributed throughout the water. There is a descending liquid film between the plugs and the tube wall and they move upward with a hemispherical top and a flat bottom.

**Churn flow**: By increasing the velocity of the air-water mixture, the slug flow’s structure becomes very unstable and air plugs start breaking up resulting an oscillatory motion as the water near the tube wall pulses upward and downward continuously.

![Flow patterns of the air-water two phase upward flow in a vertical tube](image)

**Figure 1.** Flow patterns of the air-water two phase upward flow in a vertical tube
Froth flow: By increasing the air flow rate in a high superficial water velocity, the plugs from the churn flow move faster, get more distorted and broken into shorter length plugs while merged in the water. This results a more homogenous churn flow with a frothy appearance.

Annular flow: The annular water film on the tube walls moving up with a more or less continuous interface to the air that is flowing up in central of the tube, while some small water droplets are still distributed in the flow of air. The concentration of the water droplets could be increased by increasing the water flow rate, so the droplets coalescence in the core will result large lumps or streaks (wisp) of water. This flow regime is so called wispy annular.

Figure 2 illustrates the development of the flow pattern for various superficial gas velocities in an air-water two phase upward flow in a vertical tube. The superficial air velocity in the left side is smaller than the one in the right side, while the small bubbles are injected. A stable bubbly flow in the left tube is occurred due to an equilibrium of bubbles coalescence and break-up. Due to the lift force, the smaller bubbles tend to move towards the tube wall, while the larger bubbles tend to move towards the center of the tube at low break-up rates at shown in the right side tube. This can result a transition from the bubbly to the slug flow and also to the other flow regimes.

Figure 2. Development of the flow pattern for two different air volume flow rates \((V_{SGL} < V_{SGR})\)
Chapter 3

Design, construction and operation of the experimental facilities

3.1. Adiabatic poly-dispersed air-water two phase upward flow

The PFD for this experimental facility is shown in figure 3. The ordinary tap water in the storage tank is pumped with a maximum capacity of 83 GPM to the loop. There are two high-accuracy digital flowmeters, one for the water flow rates from 1 to 10 GPM, and the other one from 10 to 100 GPM. A maximum superficial water velocity of 4.6 m/s can be expected in the water column upward. When the water is required to flow into the water column, the valve mounted before the filter is fully closed. Depending on the required range of the flow rate, the other one of the two control valves mounted before flowmeters has to be fully closed. There is a by-pass line right after the outlet of the pump for adjustments and control of the flow rate as it returns the unwanted amount of water to the tank. For the periodic filtration of the water to maintain its quality in an acceptable level, the pump will circulate the water trough the filtering loop while the ball valve before the mixing chamber at the inlet of the water column must be fully closed. For safety reasons, it is very important that before running the pump, the bypass valve is to be fully or at least partially opened. So, this will avoid any damages in case of probable blockage or malfunctioning of the valves or other measuring equipments in the loop.

The supplied water to the water column will move upward to the separation tank mounted at the highest level of the apparatus, will be temporarily collected and returned to the main water storage tank shortly. For the safety reasons at this part, it is always better to operate the system from a very low flow rates to the higher. Sudden entrance of high rate or high velocity water to the separation tank from the column is not recommended as it can cause flooding. The level of the water in the storage tank is better to be higher than the elevation of the outlet of all return lines. This will avoid a high turbulent water mixed with the unwanted entrained air bubbles to the suction line of the pump.
The filtered pressurized supplied air is entering to the corrosion-resistant exhaust muffler mounted inside the mixing chamber vertical to the flow of water. This will provide a polydispersed bubbly flow into water. The control valve mounted on the air flowmeter will allow us to change the rate of flowing air to the system, so we can see the transitions from bubbly to slug, churn and annular flow. The air entered into the water column will be separated and vented in the disengagement zone at the top.

A drainage line before entering the pump has been considered for the emergency cases and immediate required discharge of the water or for renewal of the water. Figure 4 shows some views of the actual constructed apparatus in the Thermal-Hydraulic lab at CCNY/CUNY.

**Figure 3.** The process flow diagram (PFD) for the air-water two-phase flow in a vertical column

A steel structure is fabricated using angle irons to carry the entire system on a movable cart with the height of 17 feet. The detailed specification of the main components in this apparatus are:
- A Vertical Polyethylene Tank 130 Gallon Capacity, 29" Diameter X 51" Height, filled with the ordinary tap water
- Extended-Life Type 316 SS Centrifugal Pump 1 hp, 115/230 VAC, 59 Feet of Head Max, for the circulation of the water in the loop
- Heavy Duty Rectangular Polyethylene Batch Can 2 Gal, 10-1/8" L X 10-1/8" W X 9-1/8" H, 3/16" Wall, mounted at the top of the apparatus to separate two phases of water and air, so air will be vented out and water will be returned to the storage tank
- HI-Accuracy Digital Flowmeter/Totalizer 316 Stainless Steel, 1 to 10 GPM, 1/2" NPT Female, and 10 to 100 GPM, 1-1/2" NPT Female, to measure the lower water flow rates
- Pulse Output Module for PVDF, Brass, SS, interfacing the data acquisition system and HI-Accuracy Digital Flowmeters/Totalizers
- Panel-Mount Flowmeter for Air W/Brass Valve, 4.2-42 SCFM, 1/2" NPT Female, , to measure the air flow rates
- Clear Cast Acrylic Tube 2" OD X 1-1/2" ID, 5' Length each, connected to each other by the same material flanges and mounted vertically to the outlet of the pump as the test section for the air-water two-phase flow
- Corrosion-Resistant Exhaust Muffler 3/4" NPT Male, 438 Max SCFM, 2-1/4" Height, mounted in a lab fabricated mixing tee (chamber) to generate air bubbles from the supplied compressed air into the water column upward
- Low-Pressure PVC Ball Valve 1-1/2" NPT Female, White, used in the water loop as shown in the PFD in the figure 3
- Cart-Smart Caster Swivel and rigid, 4" X 1-3/8" Iron Wheel, Brake, 450# Capacity
- Low-Pressure Bronze Globe Valve 1-1/2" and 1/2" NPT Female, to control the water flow rate entering the water column from the pump
- Flexible Std-Wall Clear PVC Unthreaded Pipe 1-1/2" Pipe Size, 10' Length each, Schedule 40, for connections between valves and other equipments in the water loop
- Space-Saver Oil Removal Air Filter/Regulator 1/2" Pipe, 166 Maximum SCFM @ 100 PSI, to filter the supplied compressed air
- Water Filter Clear Housing, Sediment & Rust, 3/4" NPT Female, 20 GPM, for the periodic filtration of the water
Figure 4. The constructed facility for the vertical upward air-water two-phase flow at CCNY
3.2. Mono-dispersed air bubble in an upward annular water flow

This facility has been designed and constructed to conduct the research and simulation of the sub-cooled flow boiling in the reactor. The figure 5 illustrates the PDF of the current apparatus to be used for required tests. The flow regime can range from single-phase liquid (deionized, degassed water) to a dispersed bubbly flow, upward and in a vertical orientation. In the test section, where the mono-dispersed bubbly flow is occurred, the inner tube (Inconel, OD=3/16") is machined to create a 400 micron size hole to disperse the air bubbles into the liquid flow. The test section is approximately at $L/D$ of 45, where $L$ is the length from the bottom of the transparent outer tube (poly-carbonate, ID=3/4", t=1/16") and $D$ is the poly-carbonate tube's inner diameter. There is a gap of 9/16" between the inner and outer tubes. Figure 8 shows the actual constructed facility for the vertical upward air-water two-phase flow experiments at CCNY/CUNY.

**Figure 5.** The process flow diagram (PFD) for the air-water two-phase flow in the annulus
A transparent water storage tank (2 Gallon capacity) has been installed. This will allow the user to see and control the quality of the water. It is filled with de-ionized water for the tests. In order to have a non-pulsating liquid flow in the system, a flexible impeller pump (6 GPM capacity) has been installed. These versatile pumps have a wear-resistant flexible rubber impeller that can handle suspended solids, as the tracer particles will be used for the PIV measurements. The flow rate of the liquid phase is controllable by the by-pass valve and also the flow regulating needle valve. A high accuracy digital flowmeter (1-10 GPM) has been installed to measure the flow rate of water entering the annulus from the bottom. The maximum bulk velocity of water in the annular channel can vary up to 1.48 m/s by increasing the water flow rate. An air/water separation sheet has been installed vertically inside the water storage tank to avoid re-entering of the returning bubbles from the test section to the tank and pump’s suction line.

Air is injected into the Inconel tube from the top, using a programmable variable speed syringe pump. In order to avoid the oscillations of the air bubbles, a grooved filling rod (1mm thick and depth) is inserted into the Inconel tube from the top to reduce the volume of passing air through the tube reaching the micron size air ejection hole. The bottom part of the test section in the Inconel tube is filled and sealed by a rod. Figures 6 and 7 show the formation, detachment and movement of bubbles in upward water flow with 1 m/s velocity and the time interval is 1 second and 2 m/s and the time interval is 1.5 second, respectively.

Figure 6. Sequential images of formation of bubbles inside the annulus (VSL=1 m/s, t=1 s)
The PIV system available for the measurements is a La-Vision (FlowMaster 2-D), 532 nm double Nd:YAG high energy pulsed laser (Litron Nano S 30-15 with 2 x 30 mJ/pulse with pulse rate up to 15Hz) would be used as the illumination source for PIV measurements. It will be synchronized with the high speed video camera to visualize the movement of the hollow glass spheres (seed particles with SG=1.05) inside the water, while the test section is illuminated by the green laser plane. In order to manipulate the laser beam and create the appropriate laser plane for PIV measurements, the high-energy optics will be used.

A high-resolution (1280 x 800 pixels) high speed (500,000 fps) digital video camera (Phantom V-310) is used to capture the images of the flow fields, as it has two modes of operations. The ‘triggered’ mode that has a 15 (Hz) framing rate in which it allows us to capture two consecutive frames with a very short controllable time delay. The other operation mode is the normal or continuous mode which has 30 (Hz) framing rate. The originated synchronization signals from the camera will pass through a pulse generator and trigger the laser.
Figure 8. The constructed facility for the annular upward air-water two-phase flow at CCNY
Chapter 4

Discussion, conclusions and recommendations

Flow regime information in a vertically upward boiling water flow inside a circular tube, can be obtained from experiments on non-boiling adiabatic air-water two phase flow. The successful design, construction and operation of the experimental facility will help us to obtain a set of accurate and reliable data to provide the empirical correlations compared and validated by mathematical modeling and simulations in detail.

The constructed experimental facilities described in the thesis report enable us to perform a set of successful experiments and data acquisition since they have been designed with all required technical and operational provisions. One of the most important operational provisions in these facilities is their vibration free structures. The most sensitive parts of the apparatus is the test section. In both systems, a proper vibration-damping parts have been used to stabilize the test section during the imaging periods.

In order to minimize the optical distortion effects resulting from the geometry and curvature of the tubes in the test sections, it is recommended to use an optical correction box around the imaging zone. In order to solve the problem with tube's curvature and distortion in the test sections, since there are some limitations regarding the use of the "calibration target" for the PIV measurements, a good suggestion is to use the FEP (Fluorinated ethylene propylene) tube in which the refractive index of FEP is 1.338, which is nearly equal to that of water, 1.333.

At the end, the discussed constructed facilities in this report were designed and constructed in a cost-efficient way. A good design of the experimental set-up involves correct and reliable mechanical, electrical and instrumentations relevant calculations to make it as easy as possible for accessing, maintaining, future developing and operating with the minimized risk factors.
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