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A Laser/Fluorescent Dye Flow Visualization Technique Developed for System Component Thermal Hydraulic Studies

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Summary

A novel laser flow visualization technique is presented together with examples of its use in visualizing complex flow patterns and plans for its further development. This technique has been successfully used to study 1) the flow in a horizontal pipe subject to temperature transients, to view the formation and breakup of thermally stratified flow and to determine instantaneous velocity distributions in the same flow at various axial locations; 2) the discharge of a stratified pipe flow into a plenum exhibiting a periodic vortex pattern; and 3) the thermal-buoyancy-induced flow channeling on the shell side of a heat exchanger with glass tubes and shell. This application of the technique to heat exchangers is unique. The flow patterns deep within a large tube bundle can be studied under steady or transient conditions. This laser flow visualization technique constitutes a very powerful tool for studying single or multiphase flows in complex thermal system components.

1. Introduction

Argonne National Laboratory, in its Flow and Heat Transfer Test Facility, is conducting a wide spectrum of studies directed at improving the thermal-hydraulic performance of thermal system components.[1] Components such as heat exchangers, steam generators, piping, mixers, storage tanks, valves, pumps, and single and multiphase energy transport fluids are common building blocks associated with seemingly diverse thermal systems such as power plants (nuclear and coal), domestic or industrial heating and cooling systems, oil refineries, food processing, and chemical materials processing. Improvement of the performance of these systems and development of new systems are intimately related to the level of understanding engineers have of the complex flow patterns occurring in the components that make up these thermal systems, and to their understanding of the influence of flow behavior on such quantities as pressure drop and heat and mass transfer.

Over the years, flow-visualization research has taken various forms. For the most part, however, investigators have been unable to see what really was happening during the flow and to quantify what information they were able to obtain.

This problem became particularly acute as the researchers observed turbulent flows or the complex environment of multiphase flows--i.e., flows that involved two or more constituents, such as a carrier liquid plus particulate matter, either solids or gas bubbles.

An additional complication arises because many flows of interest are transient. In the past, the only way to obtain sufficient quantifiable velocity data was to repeat an experiment many times. Even then, the information obtained represented point measurements. Not only was the study of velocity effects time-consuming, but phase differences between points being measured caused information to be lost.

2. Description of Technique

An argon-ion laser, in conjunction with a cylindrical optical lens, is used to create a thin intense plane of laser light for the illumination of various flow tracers in precisely defined regions of interest within a test article that has windows.[2,3] Both fluorescing dyes "tuned" to the wavelength of the laser light (to maximize brightness and sharpness of the flow image) and small, opaque, nearly neutrally buoyant polystyrene spheres (to ensure that the particles trace out the fluid motion) have been used as flow tracers. The patterns traced out by the flow tracers are recorded photographically by a high-speed video camera recorder system looking in a direction normal to the plane of the laser light. Because of the low "light noise" levels produced by scattered light coming directly from the laser-light source, as well as from the tracers not directly in the light plane, and because of the very precise spatial resolution, this technique is capable of delineating extreme detail in flow patterns over large illuminated areas.

Currently, a Spin Physics SP-2000 motion analysis system is used to record the fluid motions at frame rates as high as 2000 frames/sec in full frame mode, or up to 12000 frames/sec in partial frame format. Even for high-speed flows, the video camera can obtain discrete images of individual moving particles. In addition, the results can be viewed immediately, eliminating the wait needed by developing photographic film. A 238-horizontal- by 192- vertical-pixel CRT screen allows the resolution needed to study behavior such as the rotation of individual particles and the interactions of various particles. The motion analysis system is able to digitalize video frames and download them to a dedicated computer for image processing. At present, this capability of the motion analysis system has not been fully implemented. The velocity profiles presented herein were obtained manually by movement of a recticle on the Spin Physics SP-2000 and recording the XY location.

Without the dyes and flow tracers, the transparent flow would, of course, be invisible. The particular, 2', 7' Dichlorofluorscein dye (1 gm/3 gallons of water) has been chosen for maximum brightness and sharpness of the flow image at the wavelength of the argon-ion laser light. Recently, new fluorescent-dyed particles, provided by Eastman Kodak, that shift the frequency of the laser light toward the red end of the spectrum have been used. The dyed particles fluoresce at the blue-green end (488 to 512 nm) of the laser's spectrum, but they emit radiation closer to the red end (600 nm). The maximum sensitivity of the motion-analysis system is in the red end of the spectrum. On the other hand, if the flow is multiphase, as in a lightly loaded slurry, the actual motion of the particulate phase is visible. Tracers are not needed. For a heavily loaded slurry, we have matched indexes of refraction for the particles and the fluids to allow the analysis system to see into the flowing liquid.

There are basically three types of information that can be obtained: qualitative information (i.e., pictures of flow patterns), streakline or streamline information, and finally individual particle track information. Examples of the use of each type of information is presented in the following section.

3. Examples

Certain nuclear reactor operating conditions can cause coolant flow to be convected back into the reactor outlet nozzle/piping region and to be back-flushed into the reactor outlet plenum. The preceding results in a temperature difference between pipe inflow and plenum. This temperature difference causes buoyancy forces that, if large enough, can cause (a) a pipe backflow recirculation loop, and (b) a thermal plume in the plenum. Both phenomena have been studied because they can produce undesirable pipe, nozzle, and plenum wall thermal distributions, and hence undesirable thermal stresses.

A buoyancy effects tank (BET) was constructed as part of the Argonne National Laboratory (ANL) Mixing Components Test Facility (MCTF) to investigate this flow phenomenon. The test section, shown in Fig. 1, is a clear-acrylic, horizontal, 4.64-m-long, 0.102-m-i.d. pipe connected to a 900-gal plenum. The MCTF data acquisition system is used in the BET operation. Fast response thermocouples (~10 ms) measure the temperature distributions throughout the pipe and the downstream reservoir. Fluorescent dye (2', 7' Dichlorofluorscein) was used to visualize thin planes of the flow field.

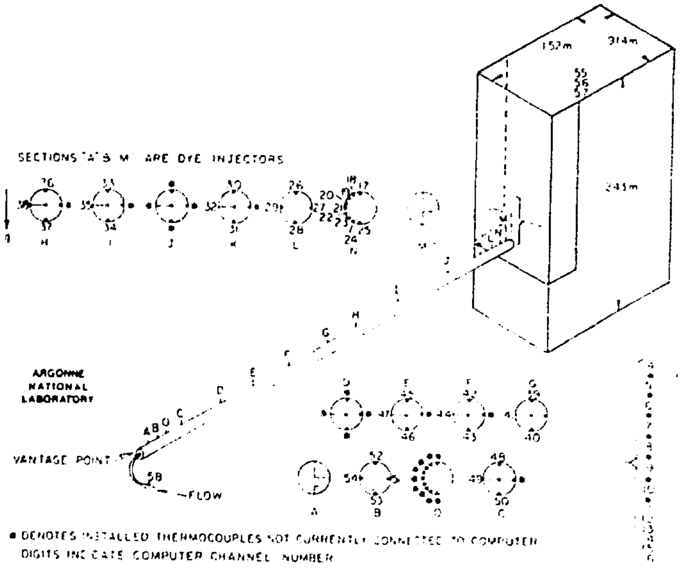

Fig. 1

Instrumentation locations

Vortex shedding was observed in the plume as the hot (~51°C) water exited the horizontal pipe into the plenum filled with cold (~15°C) water. Large, low-frequency (~0.5 to 0.8 Hz) eddies were formed along the lower edge of the plume, similar to Kelvin Helmholtz instability generated vortices, and smaller, higher frequency eddies were formed at the upper corner of the pipe/plenum interface. The vortices generated along the bottom edge of the plume break up on penetration of the thermocline formed in the plenum. Later, when the thermocline is below the eddy-formation zone, the behavior of the vortices returns to its original pattern. Figure 2 is a photograph of this vortex flow pattern. The hot water is indicated by the light, fluorescent dye; the cold water is the dark, undyed region. A 4-mil, fast-response (~10-ms), copper Constantan thermocouple was positioned in the large eddy pattern to measure the temperature response caused by the observed flow pattern. Large, quasi-periodic temperature fluctuations of the order of 76% of the available temperature difference at that elevation occurred for test BETC4 with Re = 7400 and Ri = 4.3. A power spectral analysis is shown in Fig. 3. The frequency of 0.63 Hz determined from the thermocouple response compares favorably with the preliminary frequency estimate of 0.5 to 0.8 Hz from the observed flow patterns.

In summary, thermal plume large-scale vortex patterns have been shown to cause large-amplitude thermal oscillations at low frequencies, which can give rise to thermal stresses in surfaces such as plenum walls etc. Cracks and component failure can result if the magnitude and frequency of the thermal oscillations are sufficiently large. The qualitative information provided by the dyed flow yielded useful information concerning the frequency of oscillation and, even more importantly, the mechanisms causing the oscillations.

Additional tests have been conducted in the BET. At two pipe axial measurement locations in the stratified recirculation zone (see Fig. 2), temperature and velocity distributions were measured simultaneously across the pipe diameter in the vertical symmetry plane. The velocity distribution was measured using neutrally buoyant fluorescent particle flow tracers (<50 μm) in conjunction with laser illumination and a Spin Physics Motion Analysis Video System. Fluorescent particles were introduced upstream in the stratified pipe flow, and video pictures were taken at 200 frame/s at the primary measurement locations. The camera speed was fast enough to stop each particle. By tracking individual particles over a number of video frames, the velocity at a particular radial position was determined. The velocity distribution and accuracy bounds shown in Fig. 4 were obtained by tracking individual particles at various radial positions. Some advantages of this visualization technique are the ability to measure quantitatively an instantaneous global velocity distribution (not just a point velocity), to obtain clear, unambiguous images due to the thin plane of illuminated particles, and to make inobtrusive measurements (flow field being measured is not disturbed).

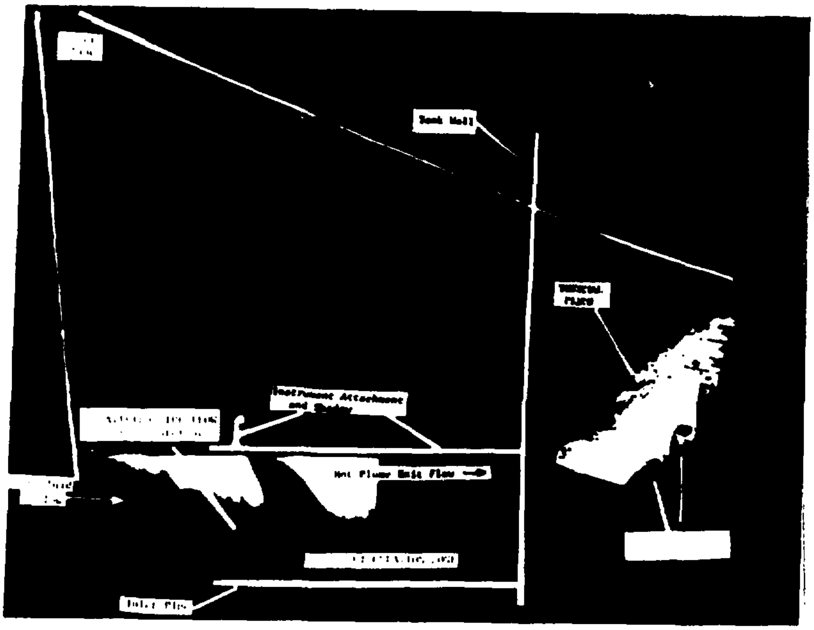

Fig. 2. Photograph of hot flow from horizontal pipe emptying into plenum showing both the cold (dark) recirculation region in the pipe and the vortex pattern in the thermal plume in the plenum.

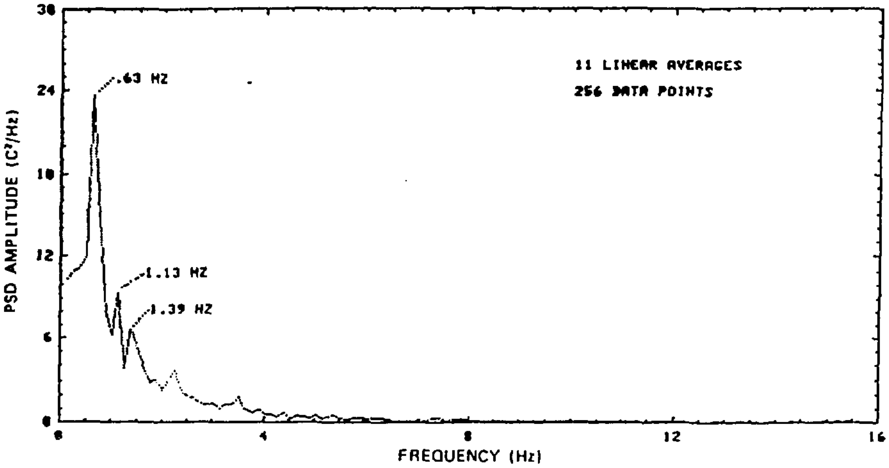

Fig. 3. Power spectral analysis of response of thermocouple positioned in vortex pattern of thermal plume with linear averaging.

Eastman Kodak participated with ANL in developing the most suitable combination of the type of particle (i.e., size and density) and dye (i.e., wavelength of fluorescing optimum for the ANL argon laser and video camera) for the present application. The Spin Physics Motion Analysis System has been connected to the Mixing Components Test Facility data acquisition system and efforts are under way to perform computer analyses of the video images. The current data confirm the workability and strength of this system under development.

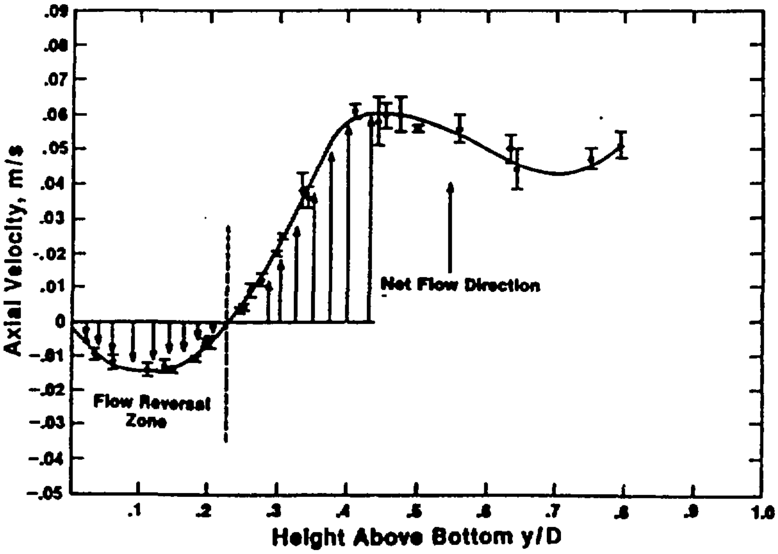

Fig. 4. Horizontal pipe flow velocity in a vertical symmetry plane in the region of the buoyancy-induced recirculation zone, showing the cold reversed flow region at the bottom of the pipe and velocity gradient in the shear zone.

Temperature profiles were measured with three fast-response, copper-constantan thermocouples mounted along a 0.31-cm-diam support rod spaced 2.54 cm apart. The rod was moved by means of a micrometer depth gauge. Simultaneous laser pipe flow visualization velocity and temperature profiles are shown in Fig. 5 for the same axial location in the horizontal pipe, near the plenum. The horizontal axis is the radial distance from the pipe centerline, nondimensionalized with respect to the pipe diameter. Note that the shear layer (i.e., region of steep gradient in velocity and temperature) extends from a radial location of -0.35 to -0.1 (a quarter of the pipe diameter). Also, the point of zero velocity (i.e., the eye of the recirculation zone) is in a region of large temperature gradient. Both temperature and velocity gradients can be determined from the above data and used to calculate the gradient form of the Richardson number, the ratio of buoyancy to inertia forces.

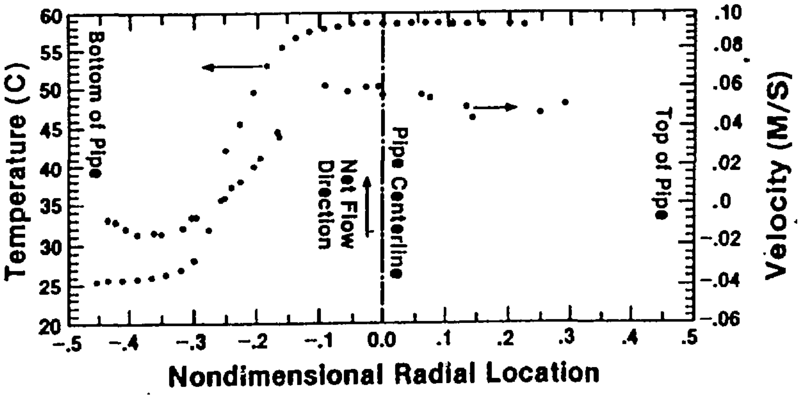

Fig. 5. Simultaneous velocity and temperature profiles occurring in a stratified horizontal pipe flow, vertical summetry plane.

Results from tests have been analyzed to establish a criterion for determining the conditions for laminarization of a turubulent shear zone.

Results indicate laminarization of the turbulent shear zone occurs at a Richardson number of ~0.6 based on the measured shear layer thickness as the length scale. The situation is complicated in that making the distinction between being turbulent and possessing large instability waves at the stratified interface is difficult. Suppression of the oscillatory behavior of the stratified interface due to either cause is very important since conditions conducive to thermal striping would be eliminated. The current study shows that under certain conditions these oscillations are suppressed by buoyancy forces.

Finally, particle streakline information has been used in studying thermal buoyancy-induced flow channeling on the shell side of a heat exchanger[1] with glass tubes and shell. The HX (~1 ft. dia) contained 156 tubes in a triangular pitch with full disc varying porosity baffle plates (spaced ~6 in. apart) to promote crossflow in the tube bundle. The plane of light was precisely located between rows of tubes slicing the bundle in half and viewed normal through the shell and intervening rows of glass tubes. Small plastic spheres (~20 μ were injected upstream of the heat exchanger inlet. The resulting streaklines, formed when the particles entered the plane of laser light, are shown in Fig. 6 from which an instantaneous velocity distribution can be determined. Application of this technique to heat exchangers is unique. The flow patterns deep within a large tube bundle can be studied under steady or transient conditions. By shortening the exposure time of each frame, the individual particles are frozen and appear as points, which may be tracked from one frame to another, yielding a mapping of the velocity field for a complete slice through the tube bundle.

The technique has also recently been extended to study highly loaded particle suspensions by matching refractive indices of fluid and particle phases. Dyed particles which were made of the same material as the loaded particles were seeded into the flow as tracers. The experiments[4] proved the feasibility, at particle concentrations of 30%, of the measurement of velocity and concentration profiles. The presence of impurities and voids in the particles limited the maximum useful particle concentration and the minimum size of the particles by introducing light scattering optical noise which blurs the images.

Thus, the flow visualization technique presented herein and high-speed videography in conjunction with a, as yet to be fully implemented, computer image processing is an extremely useful tool which will significantly accelerate our understanding of turbulence and multiphase flows in complex thermal system components.

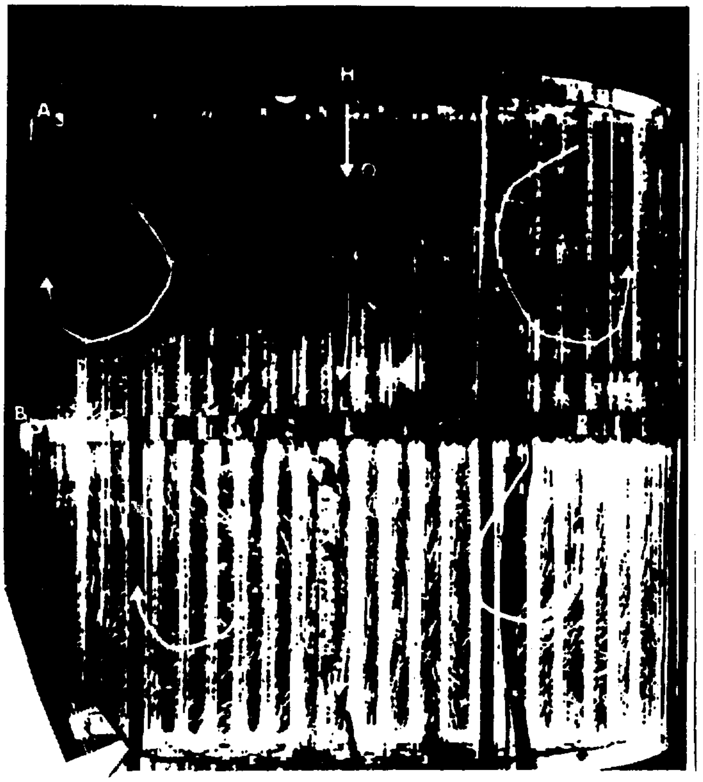

Fig. 6. Tube bundle shell flow patterns: thermal transient passing by field of view, strong buoyancy-induced flow channeling.

5. Acknowledgements

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6. References

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