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VISUALIZATION OF MIXED CONVECTION FLOWS IN VERTICAL, HORIZONTAL, AND INCLINED PIPES

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ABSTRACT

An experimental apparatus for visualization of laminar mixed convection flows in vertical, horizontal, and inclined pipes is described. Two key elements of its design allowed, for the first time, flow visualization over the entire heated portion of the test section: a thin, electrically conductive, gold-film heater, suitably attached to the outside surface of a Plexiglas pipe, and about 80% transparent to light; and enclosure of this pipe within a larger concentric Plexiglas tube, and evacuation of the air in the annular space to achieve an essentially transparent and excellent insulation of the heated portion of the inner pipe. A dye injection technique was used to visualize the mixed-convection flow patterns. The flow-visualization photographs revealed the following: (i) a steady recirculating flow pattern which was followed by laminar flow instability in the vertical tubes; and (ii) dual, essentially symmetric, and steady spiralling flow patterns in the inclined and horizontal tubes. Some of these results were qualitatively similar to earlier numerical predictions in the published literature. The results are presented and discussed in this paper.

INTRODUCTION

Mixed convection heat transfer is commonly encountered in engineering equipment and in the environment. One example is closed-loop thermosyphons. Other examples include flows inside tubes used in flat-plate solar collectors and in emergency cooling systems for nuclear reactors. The design of such equipment is a multi-parameter problem that is best solved using an astute combination of computer simulations and focused experiments, before the building and refining of prototypes. Experimental apparatus and procedures for visualization of laminar mixed convection flows in vertical, horizontal, and inclined pipes are proposed in this paper. They are intended to facilitate the aforementioned complementary experimental and numerical approaches to the design of heat transfer equipment.

The study of mixed convection heat transfer in vertical, horizontal, and inclined pipes, subjected to a uniform wall heat flux, has been given considerable attention in the literature. A review of studies of mixed convection in vertical tubes has been provided by Jackson et al. (1989). Scheele et al. (1960) and Scheele and Hanratty (1962) investigated the effects of natural convection on the transition to turbulence in upward and downward flow of water in a vertical pipe. They used dye injection to visualise the flow, but since they employed only opaque pipes, the motion of the dye could be observed only in the vicinity of the outlet plane of the heated pipe. Other experimental investigations of such mixed-convection phenomena include the works of Brown and Gauvin (1965a, 1965b), Barozzi and Pagliarini (1984), Tanaka et al. (1987), Bernier and Baliga (1992a), and Celata et al. (1998). Mohammed (2008) experimentally investigated laminar mixed convection heat transfer in a vertical pipe under buoyancy-assisted and buoyancy-opposed conditions. Flow visualization was not conducted in any of the aforementioned experimental investigations, except in the work of Bernier and Baliga (1992a).

Bernier and Baliga (1992a) developed and implemented a technique for subjecting a length of pipe to a uniform heat flux boundary condition, whilst maintaining the heated length translucent, thereby permitting flow visualisation, using dye injection (for example). Their technique, which was inspired by the earlier works of Hippensteele et al. (1983) and Baughn et al. (1985), is based on the use of a thin, semitransparent gold-film electrical heater, glued on the *inside* surface of a Plexiglas pipe. It allows the back surface of the polyester substrate of the gold-film heater to come into direct contact with the fluid (water), minimizing heat-loss to and conduction redistribution within the pipe wall. However, with their technique, it is difficult to construct a durable heater, as the two copper electrodes needed for powering the heater film cannot protrude into the pipe. So the contact between the electrodes and the gold-film heater is quite fragile, leading to frequent failure (burnout) of the gold-film heater. It should also be noted that Bernier and Baliga (1992a) used opaque insulation, which was momentarily removed from a fraction of the heated length of pipe to enable flow visualisation.

Experimental investigations of mixed convection in straight horizontal pipes include the works of Metias and Eckert (1964), McComas and Eckert (1966), Petukhov et al. (1969), and Morcos and Bergles (1975), amongst others. Flow visualization was not carried out in any of these studies. Mori and Futagami (1967) conducted mixed convection experiments in a horizontal tube, with air as the working fluid and a double-transparent-pipe heated test section, and used smoke injection to obtain a few flow visualization photographs.

For inclined pipes, the number of experimental investigations is quite limited. An example is the work of Leong et al. (1991), who used water as the working fluid and undertook some flow visualisation work. However, their heated test section was opaque, so the flow visualization was done only in an unheated transparent portion of the pipe.

There are many numerical studies of laminar and turbulent mixed convection in pipes. Examples of such studies include the works of Iqbal and Stachiewicz (1966), Cheng and Hong (1972), Cotton and Jackson (1990), Bernier and Baliga (1992b), Wang et al. (1994), and Laouadi et al. (1994).

Evans and Grief (1997) numerically studied buoyant instabilities of downward flow in a symmetrically heated vertical channel. A numerical study of the linear stability of mixed convection flow in a vertical pipe has been conducted by Su and Chung (2000).

The primary objective of the work presented in this paper was to design, construct, and demonstrate the use of an experimental apparatus for visualization of laminar mixed convection flows in vertical, horizontal, and inclined tubes of circular cross section. The following two key elements of its design allowed, for the first time, flow visualization over the entire heated portion of the test section: a thin, electrically conductive, semitransparent gold-film heater, suitably attached to the outside surface of a Plexiglas pipe; and enclosure of this Plexiglas-pipe-gold-film assembly within a larger concentric Plexiglas tube, and evacuation of the air inside the annular space between the tubes, to achieve an essentially transparent and excellent insulation of the heated tube. Details of this special design of the proposed experimental apparatus are discussed later in this paper.

In the proposed flow visualization apparatus, as the transparent gold-film heater is glued onto the *outer* surface of the Plexiglas pipe, two copper electrodes could be firmly fastened to it. Thus, in contrast to frequent burn-outs of the gold-film heater used in the experiments of Bernier and Baliga (1992a), the gold-film heater used in this work performed continuously during the entire course of the investigation, over a period of many months, without burning out. However, since the gold-film heater is glued to the outer surface of the pipe, conduction redistribution of the applied heat flux in the pipe wall is more appreciable than that in work of Bernier and Baliga (1992a). In this context, it should be noted that heat conduction in the walls of pipes conveying fluids is relatively straightforward to account for in numerical simulations [Bernier and Baliga (1992b); Laouadi et al. (1994)]. Moreover, with proper selection of materials and dimensions, the effects of wall conduction can be minimized.

NOMENCLATURE

c_p	[J/kg.K]	Specific heat at constant pressure of distilled water
D	[m]	Internal diameter of the heated Plexiglas pipe
Gr	[-]	Grashof number (based on heat flux): $Gr = (\rho^2 g \beta q_w^{"} D^4)/(\mu^2 k)$
k	[W/mK]	Thermal conductivity of distilled water
Pr	[-]	Prandtl number: $Pr = (\mu c_p)/k$
$q_w^{"}$	[W/m^2]	Heat flux applied to the outer surface of the heated Plexiglas pipe
Q	[m^3/s]	Volume flow rate of the working fluid in the test section
Re	[-]	Reynolds number: $Re = \rho U_0 D/\mu$
T	[ºC]	Temperature
$T_{b,i}$	[ºC]	Inlet bulk temperature of the working fluid
$T_{b,o}$	[ºC]	Outlet bulk temperature of the working fluid
U_0	[m/s]	Mean velocity of the working fluid in the test section
z	[m]	Axial coordinate
Greek symbols		
α	[degree]	Angle of inclination of the heated Plexiglas tube to the horizontal
β	[1/K]	Thermal volumetric expansion coefficient of distilled water
μ	[kg/m.s]	Dynamic viscosity of distilled water
ρ	[kg/m^3]	Density of distilled water

OVERVIEW OF EXPERIMENTAL APPARATUS

A schematic illustration of the experimental apparatus is given in Figure 1. It consists of three main sections: (1) working fluid (distilled water) circuit; (2) a vacuum circuit; and (3) a dye injection circuit. For ease of discussion, the heated section of pipe, over which the flow-visualisation was conducted, will be referred to as the test section. A semitransparent gold-film heater is fastened to the test section. Details of the design and construction of the gold-film heater are discussed in the next section.

Working-fluid circuit: This circuit consists of elements # 1, 2, 6, 7, 9, and 10 in Figure 1. A pump was used to draw the working fluid (distilled water) from a constant-temperature water bath (Neslab, Model RTE-221), and feed it to a constant-head tank. The working fluid from the constant-head tank flowed into the test section, through a tube with a coarse-adjustment ball valve. An inner tank maintained the water level constant in the constant-head tank, by allowing any excess water to flow back to the water bath. After flowing through the test section, the working fluid returned to the constant-temperature bath, which was capable of maintaining the water temperature to within ±0.02ºC of the set value. The entire apparatus was insulated very well. The flexible tubes (PVC) were insulated with two layers of half-inch foamed plastic pipe insulation (Armaflex; thermal conductivity of k=0.04 W/mºC). The temperature of the water at the inlet of the test section could thus be controlled to within ±0.05°C.

The flow rate through the test section was controlled using a combination of a coarse-adjustment ball valve and a fine-adjustment globe valve. To minimise air entrainment in the working-fluid circuit, simple nozzles and diffusers were constructed using plastic water funnels and filtering cloth. They were inserted into the respective inlets and outlets of the tubes entering the constant-temperature bath and served to calm the flow. This provision dramatically reduced gurgling in the bath and practically eliminated the air bubbles that would otherwise accumulate in the test section.

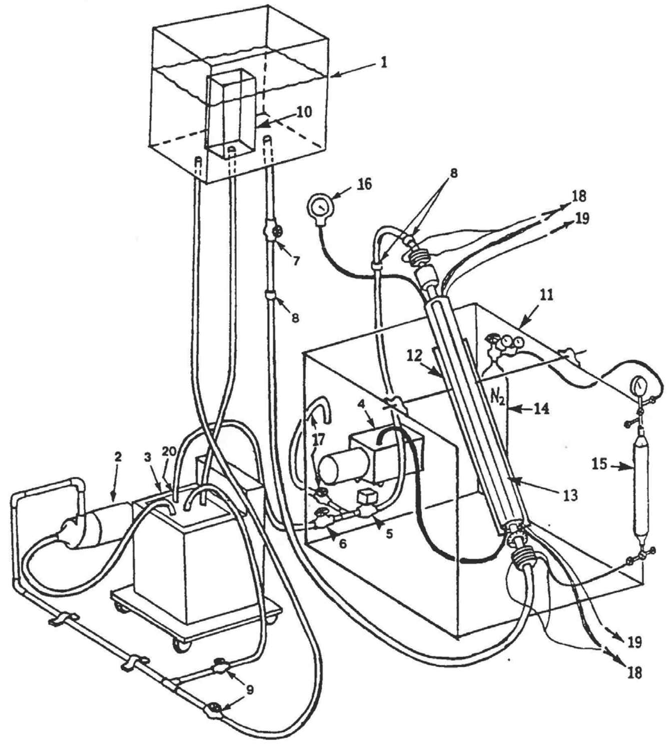
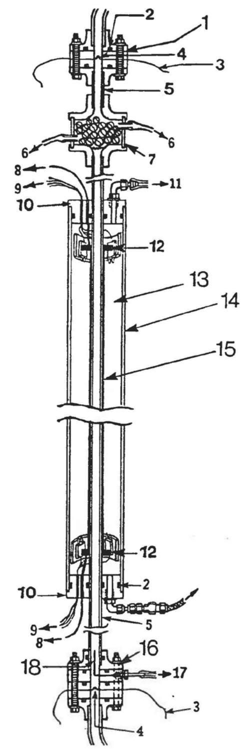


Figure 1 Schematic illustration of the experimental apparatus: 1 constant-head tank; 2 water pump; 3 constant-temperature water bath; 4 vacuum pump; 5 solenoid valve; 6 fine-adjustment globe valve; 7 coarse-adjustment ball valve; 8 pipe connectors; 9 ball valves; 10 inner tank (for collecting overflow); 11 metal frame; 12 inclinable platform; 13 test section and vacuum chamber; 14 pressurized nitrogen cylinder; 15 dye-injection apparatus; 16 vacuum pressure gauge; 17 bypass gate valve and pipe; 18 thermocouple wires (to data acquisition system); 19 electrical lead wires (to DC power supply); and 20 exit of primary fluid circuit.

Test section and vacuum circuit: These elements are indicated by the number 13 in Figure 1, and a detailed view is provided in Figure 2. A Plexiglas tube (1.905 cm inside diameter, 2.54 cm outside diameter, and 1.65 m long) was used to construct the test section. It was connected to flexible tubes by coupling flanges on both its ends, as shown schematically in Figure 2. The coupling flanges were designed to minimize flow disturbances, and accommodate thermocouple wires and a dye-injection needle.

The test section was enclosed inside a larger Plexiglas pipe (#14, Figure 2) of 8.89 cm inside diameter, 10.16 cm outside diameter, and approximately 1.22 metres long. The annular space between the test section and this larger pipe (#13, Figure 2) was closed at both ends by round Lexan caps, and connected to a vacuum pump through a compression fitting in the bottom cap. All Plexiglas flanges and joints were sealed with precision O-rings, and designed to permit differential thermal expansion of the mating pieces. During the experiments, the air in the annular space was evacuated down to approximately 200 mbars, to minimize heat loss from the test section. The test-section-outer-tube assembly was mounted on an inclinable platform (# 12 in Figure 1).



No.	Part
1	Outlet Coupling Flange
2	O-Ring Seal
3	Thermocouple Lead Wire
4	Thermocouple
5	1" o.d. Plexiglass Pipe
6	Draining Port (Closed by Ball Valve)
7	Mixing Cup and Marbles
8	Electrical Lead Wire (to Power Supply)
9	Thermocouple Wire (to Data Acquisition System)
10	Lexan Cap
11	Elbow and Hose (to Vacuum Pressure Gauge)
12	Copper Electrodes
13	Annular Vacuum Chamber
14	4" o.d. Plexiglass Pipe
15	Gold-Film (Test) Section
16	Inlet Coupling Flange
17	Needle Mount and Pipe (to Dye Injection Needle)
18	Dye Injection Needle

Figure 2 Schematic illustration of the test section and related elements.

The dye-injection circuit: In this investigation, the dye injection technique described by Bernier and Baliga (1992a) was used for the flow visualisation studies. Flow visualisation was carried out by injecting a fluorescent dye (Cole Palmer Instrument Co., water-soluble fluorescent liquid dye #298-17) into the water, just before it entered the test section. The dye was injected through a needle that was installed in the bottom coupling flange (# 17 in Figure 2). Enough length of pipe from the dye-injection needle to the inlet of the test section was provided for the flow to become essentially fully developed. The dye was prepared by dissolving approximately 1.25 ml of concentrated dye in 900 ml of distilled water. Thus, the dye solution was almost completely composed of water, and it could be considered neutrally buoyant. Furthermore, the molecular diffusion rate of this dye was small enough to allow clear visualisation of the injected filaments.

The key components of the dye-injection apparatus were a nitrogen-pressurised dye reservoir, the dye-injection needle, and illuminating lights. During the flow visualisation experiments, the dye was illuminated by two four-foot long 40W black lights (Sylvania Blacklight Blue F40/BLB) mounted on the inclinable platform, on either side of the test section. Photographs were taken with the laboratory in total darkness, aside from the illumination of the dye using the aforementioned black lights.

In most cases, flow visualisation was carried out by continuously injecting a thin filament of the dye solution into the test section. However, in some experiments, with the heated pipe in the vertical orientation, the test section was flooded with dye, by increasing the pressure in the dye reservoir. This flooding allowed clearer definition of the recirculation cells (when they occurred): the full procedure is described in Bernier and Baliga

(1992a). The dye-contaminated water was not allowed to return to the working-fluid circuit. It was expelled and replaced with new distilled water.

Arrangement for inclination of the test section: The test section and the attached outer Plexiglas tube were mounted on an inclinable platform (# 12 in Figure 1). It permitted the study of the effects of inclination (with respect to the gravitational acceleration vector) on the mixed convection flow inside the test section. In this investigation, experiments were carried out for inclination angles (α) of 0° (horizontal), 30°, 45°, 60°, 76°, 87° and 90°.

GOLD FILM HEATER

A thin, translucent gold film was used to construct the heater in this work. This film is commercially available in flat sheets (Courtalds Performance Films, California; brand name AUARE-14). It consists of a thin, transparent polyester film on which a very thin, translucent, coating of gold is applied by means of a vacuum deposition technique. The gold coating is overlaid with a proprietary ceramic coating for protection against abrasion. The main characteristics of the film used in this investigation were the following: overall thickness of 0.13 mm (0.005 inches); a gold coating thickness of approximately 20 angstroms; maximum sustainable operating temperature of 100°C at the coating interface; transparency to light of 80% ±10%; and an electrical resistivity of 13.54 Ω/square ±6.2%.

Construction procedures: The procedure for constructing the heated portion of the test sections consisted of the following major steps: (i) cutting of the gold film and application of single- and double-sided adhesive tapes to it; (ii) attaching the gold film to the outer surface of the inner Plexiglas pipe; and (iii) attaching electrodes to the gold film to allow electrical connections to the DC power supply. These three steps are briefly described in the remainder of this section.

Cutting of the gold-film and application of adhesive tapes: The gold-film was cut from a sample roll 0.4572 m wide and 15.24 m long. First, strips of the film measuring approximately 15.24 cm wide and 1.22 m long were cut. These dimensions were larger than those of the final piece of the gold film that was attached to the Plexiglas pipe. These larger dimensions of the first cut were necessary for proper application of adhesive tapes. The gold side of the film was covered by single-sided adhesive tape (3M #853) over 1.078 metres of its length. At the extremities of the film, enough of the gold side was left bare to allow for proper attachment of copper electrodes. Double-sided adhesive tape (3M #9469PC) was then carefully applied over the entire length of the polyester side of the film. The techniques used in the application of these two adhesive tapes are illustrated schematically in Figures 3 and 4, respectively. In all cases, meticulous care was exercised to ensure that no air gaps were created and trapped between the gold film and the tapes.

Following the application of the adhesive tapes, the gold film was cut to the exact dimensions required for proper mounting onto the Plexiglas pipe. Its final total length, including the exposed gold surface necessary for the attachment of the electrodes was 1.14 metres. Its width was reduced to approximately 1 millimetre less than the outer circumference of the pipe (25.4 cm outside diameter), to ensure that no portion of it overlapped after mounting onto the Plexiglas pipe.

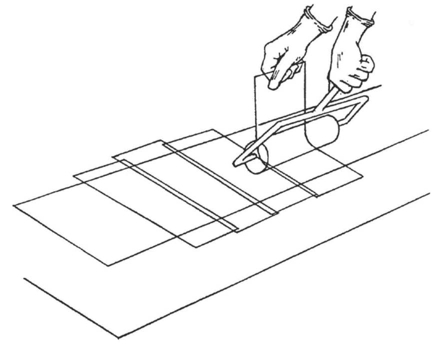
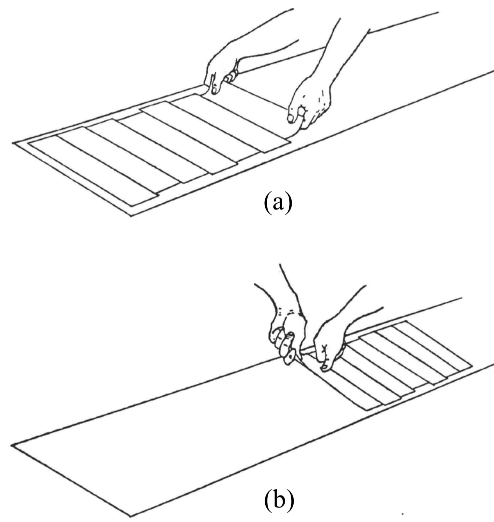


Figure 3 Schematic illustration of the application of single-sided adhesive tape to the conductive side of the gold film.



(a)

(b)

Figure 4 Schematic illustration of the application of double-sided adhesive tape to the polymer side of the gold film: (a) the edge of a strand of tape is placed alongside the edge of a neighboring strand; and (b) the strand of tape is then very carefully pressed onto the film, avoiding entrapment of air bubbles.

Attaching the gold film to the Plexiglas pipe: First, a simple jig was constructed to facilitate this task: it consisted of a 90° angle-bar made of aluminum, approximately 1.5 metres long, fastened to a large, flat, hard plywood board. A longitudinal edge of the prepared gold-film section was then aligned against the vertical shoulder of the angle-bar, keeping the side with the double-sided adhesive tape exposed. The Plexiglas pipe was then pressed securely against the vertical shoulder of the angle-bar, and then firmly pushed onto the double-sided adhesive tape. The technique is schematically illustrated in Figure 5.

Once preliminary adhering contact was made between the pipe and gold film, they were moved onto a clean rubber mat. The gold film was then completely wrapped around the pipe, by slowly rolling the pipe over the film, while pushing down firmly on it. A long, thin bead of strong two-part epoxy glue (Devcon) was finally applied over the two adjoining longitudinal edges of the gold film, which were now almost touching each other on the outer surface of the Plexiglas pipe. This epoxy ensured that the gold film did not unwrap from the Plexiglas surface during the experiments. These rolling and gluing procedures are schematically illustrated in Figure 6.

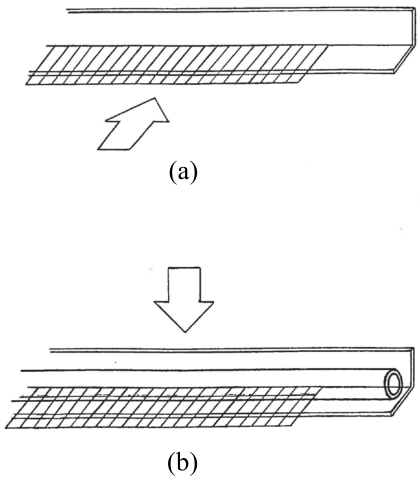


Figure 5 Schematic illustration of the mounting of the gold film onto the outer surface of the Plexiglas tube: (a) an edge of the taped film is aligned against the vertical side of an angle-bar; and (b) the Plexiglas pipe is pushed down onto the adhesive tape attached to the gold film.

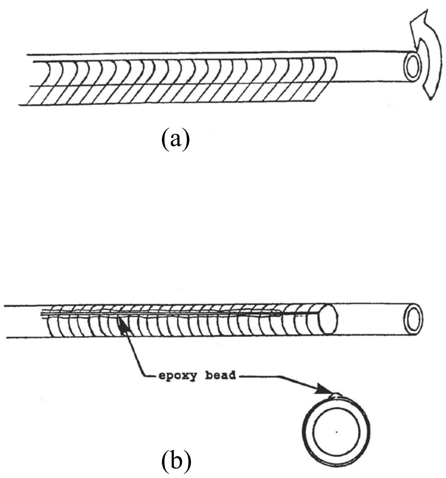


Figure 6 Schematic illustration of the wrapping of the gold film around the Plexiglas pipe: (a) first, the pipe and film are moved onto a rubber mat, and then the pipe is carefully and firmly rolled over the film; and (b) once the film is completely wrapped around the pipe, a long bead of epoxy is applied over the adjoining edges of the film, to ensure it does not unwrap during the experiments.

Electrode construction and mounting: Each electrode was made of two semicircular pieces, machined out of copper. The semi-circular contact surfaces of the electrodes were machined to a diameter 0.2 mm larger than the outer diameter of the exposed extremities of the gold film wrapped around the inner Plexiglas tube of the test section. Strands of 3M electrically conducting (copper) Scotch-brand tape were applied to the contact surfaces of the electrodes, to ensure that they fit snugly onto the gold film wrapped around the tube. The two halves of each electrode were bolted together and solidly glued to the exposed extremities of the gold film. This glue was an electrically conductive silver epoxy (Tra-Duct #2902). One such electrode mounted on to the gold film and parts of another electrode (and its constituent parts) are shown in the photograph given in Figure 7.

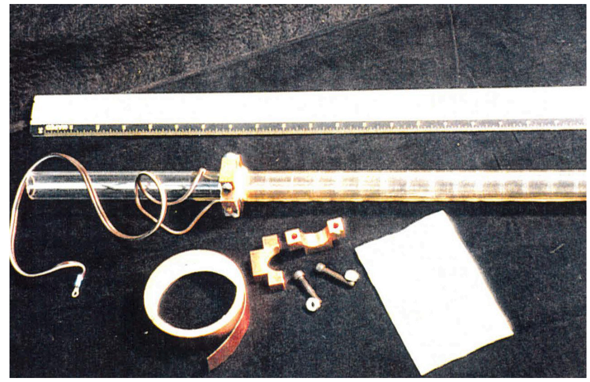


Figure 7 Photograph of a copper electrode mounted on the gold film attached to the outer surface of the inner Plexiglas tube, and parts of another electrode (and its constituent parts).

OTHER PROCEDURES AND EQUIPMENT

The acquisition of temperature data, the powering up of the gold-film heater, and the measurements of applied voltage and current were managed using a computer-controlled data acquisition system (Hewlett-Packard, model HP3497A). The supporting equipment consisted of a DC power supply (Xantrex, model XKW 300-3.5), two multimeters, and a personal computer. HP-IB interface cards were used to link these devices together.

A Plexiglas mixing cup (# 7 in Figure 2), was inserted in the fluid flow circuit, downstream of the test section, but upstream of the outlet coupling flange. This mixing cup was filled with glass marbles. It served to thoroughly mix the water before it came into contact with a thermocouple installed in the fluid flow circuit through the outlet coupling flange, and thus ensured an accurate reading of the outlet bulk temperature. The inlet bulk temperature was measured by a thermocouple inserted in the flow circuit through the lower coupling flange. Both these thermocouples are shown in Figure 2 (item # 4).

The temperatures were measured using chromel-constantan (Type-E) thermocouples. Each thermocouple bead was first covered with a dab of thermally conductive, but electrically insulating, two-part epoxy (Omega Engineering; Omegabond 101). The thermocouples were calibrated against a quartz thermometer (Hewlett-Packard, model 2804A). The uncertainty in the temperatures measured by the calibrated thermocouples was estimated to be ±0.05°C. Each thermocouple output voltage was read sixty times, and the arithmetic mean of these sixty readings was recorded. In each run of the experiment, steady-state conditions were considered to have been achieved once the readings from the inlet and outlet bulk-temperature thermocouples varied by less than ±1% over a period of ten minutes.

The mass flow rate and average velocity of the water flowing through the test section were determined using the so-called stopwatch-bucket method. To measure the flow rate, a graduated cylinder was held at the outlet of the tube returning the water from the test section to the water bath (#20, Figure 1). A stopwatch was then used to determine the rate at which water filled the cylinder. The calculated volume flow rate was divided by the inner cross-sectional area of the Plexiglas pipe to obtain the average velocity of the water. The uncertainty associated with this mass flow rate measurement was estimated to be ±1%.

The voltage and current applied to the gold-film heater were measured using two multimeters (Hewlett-Packard, model HP 3478A), one in parallel and the other in series with the gold film. The electrical resistance of the gold film was obtained by dividing the voltage by the current, and the electrical power applied to it was obtained by multiplying these two measurements.

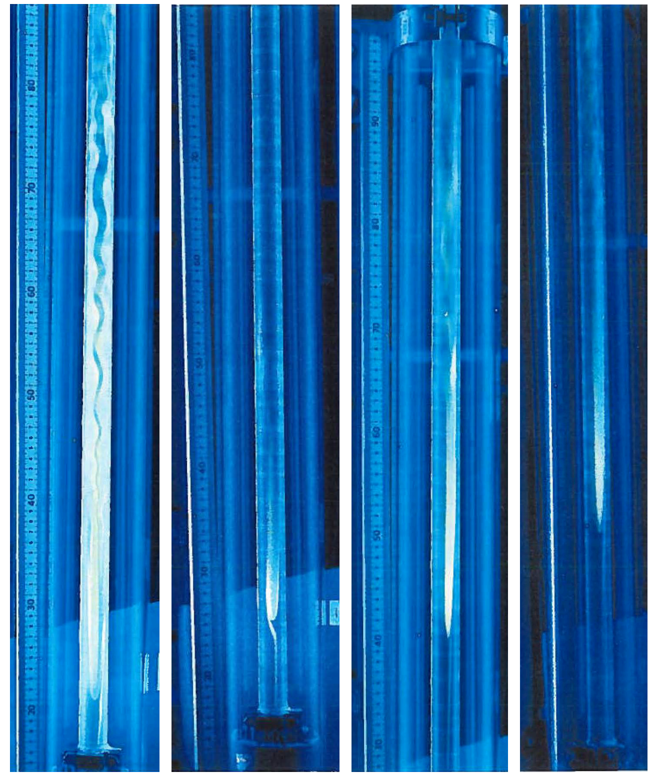
RESULTS AND DISCUSSION

In this work, 35 different flow visualization runs were conducted using the above-mentioned experimental apparatus and procedures. The values of test-section inclination angle (α) in these runs were 0° (horizontal), 30°, 45°, 60°, 76°, 87° and 90°, and the values of Gr/Re^2 ranged from 6 to 200. Here, Gr is the Grashof number, based on the heat flux applied to the heated Plexiglas pipe, and Re is the Reynolds number: these dimensionless parameters are defined in the list of notation on page 2 of this paper. In each run, the distilled water properties needed for calculating the values of these dimensionless parameters were evaluated at the arithmetic mean of the fluid bulk temperatures measured at the inlet and outlet of the heated Plexiglas tube, $T_{b,i}$ and $T_{b,o}$, respectively. In this paper, flow visualization photographs from 12 representative runs are presented and discussed. The values of experimental inputs and parameters for each of these 12 runs are summarized in Table 1.

Table 1 Summary of inputs and parameters for the flow visualization experiments

Run #	α	$T_{b,i}$ [°C]	$T_{b,o}$ [°C]	Q x 10^{-6} [m³/s]	Power [W]	Re	Gr x 10^{-5}	$\frac{Gr}{Re^2}$
1	90°	18.5	30.1	0.57	27.5	41.3	1.89	111.0
2	90°	20.4	30.2	0.96	39.5	72.1	2.95	56.8
3	90°	17.6	25.5	1.85	61.4	127.2	3.30	20.4
4	90°	20.2	30.9	2.33	104.0	174.9	7.95	26.0
5	0°	10.6	24.1	0.69	39.0	43.1	1.36	73.0
6	0°	11.6	20.7	0.51	19.8	31.1	0.60	61.9
7	0°	9.1	19.4	1.24	53.2	71.2	1.26	25.0
8	0°	8.8	20.7	1.93	96.4	112.5	2.45	19.4
9	45°	9.5	19.7	1.02	43.8	59.4	1.09	30.9
10	60°	9.7	19.7	0.93	39.1	54.2	0.99	33.6
11	76°	9.1	20.3	1.19	55.4	69.3	1.39	29.0
12	87°	8.8	20.9	1.30	65.7	76.0	1.69	29.3

Flow visualization photographs for the first four runs (Runs # 1 – 4), which were obtained with the test section in the vertical orientation (α = 90°) and the distilled water flowing upwards (bottom to top), are presented in Figure 8. These photographs

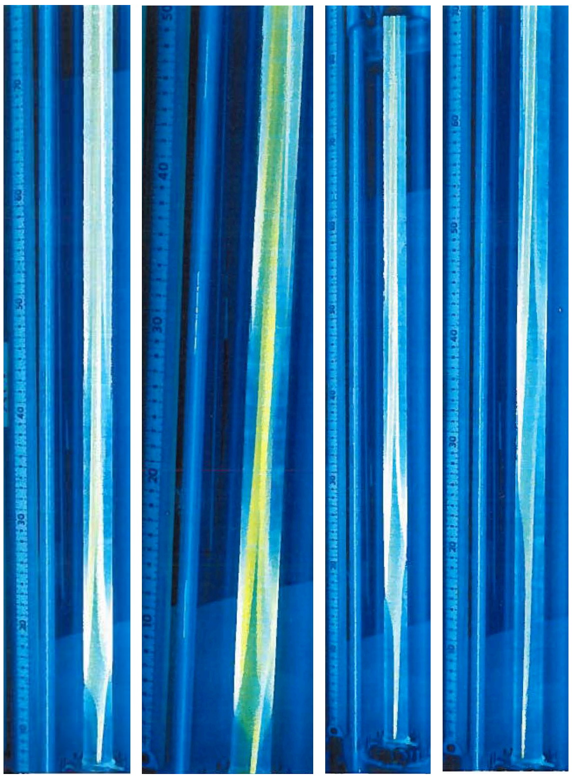


Run # 1 Run # 2 Run # 3 Run # 4

Figure 8 Flow visualization in a vertical heated pipe (α = 90°): See Table 1 for summary of inputs and parameters.

and visual observations (akin to those that would be evident in a digital video recording) revealed three distinguishable flow zones in the heated pipe. In the first zone, there is a stable recirculating fluid flow, qualitatively similar to that detected previously and also predicted numerically by Bernier and Baliga (1992a; 1992b). The second distinct zone contains wave-like fluctuations of the injected dye filament and flow, which is periodic in time, but laminar and fairly sinusoidal. This second zone can be seen quite clearly in the photograph from Run # 1, in which its length was almost 20 times the inside diameter of the pipe. This wave-like flow feature was also detected by Bernier and Baliga (1992a), but in their experiments, it occurred very close to the outlet of the heated tube (as its length-to-diameter ratio was not large enough), so only its onset could be photographed. Scheele and Hanratty (1962) also photographed a stable flow recirculation zone followed by a similar instability in upward flow inside a vertical tube subjected to a constant-wall-temperature boundary condition. In both Baliga and Bernier (1992a) and Scheele and Hanratty (1962), this second distinct zone is identified as a zone of laminar-turbulent transition. However, the flow visualization photographs obtained in this work (see Figure 8), and related visual observations, clearly showed that fluid flow in this second zone remained laminar. In the third zone, which occurs downstream of the second zone, there is irregular and disorderly motion of the dye, and the dye filament, which remains undivided (intact) in the first and second zones, separates into many thin filaments, which gradually depart from orderly wave-like motion and become entangled. However, the flow in this third zone is still laminar, as the aforementioned thin dye filaments get intertwined erratically, but do not break up and diffuse rapidly, as they would if the flow were turbulent. Thus, this third zone appears to be indicative of (or a precursor to) laminar-turbulent transition.

Another feature, an expected one, is also revealed by the photographs in Figure 8. In runs with higher values of the ratio Gr/Re^2, the natural convection effects are stronger, and the flow recirculation zone starts closer to the inlet cross section of the heated pipe, than in runs with lower values of this ratio.

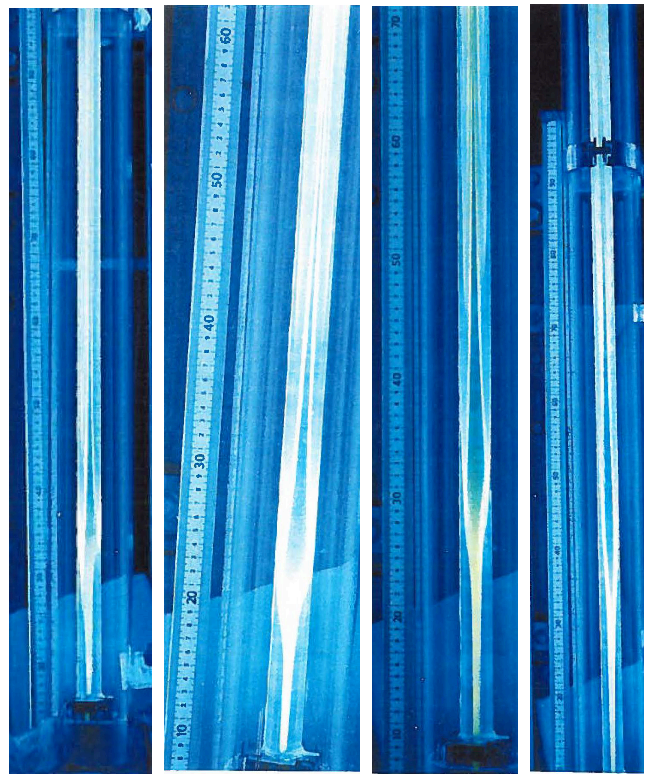


Run # 5 Run # 6 Run # 7 Run # 8

Figure 9 Flow visualization in a horizontal heated pipe (α = 0^o): See Table 1 for summary of inputs and parameters.

The flow visualization photographs obtained for runs with the heated test section in the horizontal orientation (Runs # 5 – 8) are presented in Figure 9. All of the photographs and the related visual observations revealed two, essentially symmetric, spiralling flow patterns. The dye filament injected along the centerline of the pipe drops downwards soon after it enters the heated section, and, as it approaches the pipe wall, splits into two similar streams, each of which moves upwards adjacent to the heated wall and also downstream with the main flow, in a spiral (or helical) pattern. Similar flow patterns were observed by Mori and Futagami (1967). Again, in accordance with expectations, these effects were more evident in runs with higher values of the ratio Gr/Re^2, in which the natural convection effects are stronger than in runs with lower values of this ratio. For the cases considered, the flow visualization photographs indicated no flow instabilities.

The flow visualization photographs obtained in the four runs in which the test section was inclined with respect to the horizontal are presented in Figure 10. In each of these runs, the



Run # 9 Run # 10 Run # 11 Run # 12

Figure 10 Flow visualization in an inclined heated pipe (Run # 9, α = 45^o; Run # 10, α = 60^o; Run # 11, α = 76^o; and Run # 12, α = 87^o): See Table 1 for summary of inputs and parameters.

flow splits into two essentially symmetric streams that move downstream in counter-rotating spiral (or helical) flow patterns. As was expected, these photographs also show that the observed helices of the flow patterns in the runs with lower values of the ratio Gr/Re^2 are longer (more elongated) than those in runs with higher values of this ratio. These flow patterns are qualitatively similar to those obtained numerically by Cheng and Hong (1972) and Laouadi et al. (1994). For the runs with α = 45^o, 60^o, and 76^o, the flow remained steady and laminar throughout the heated test section. Thus, in these runs, and also in the runs with the horizontal orientation of the test section (α = 0^o), the component of the gravitational acceleration vector perpendicular to the longitudinal axis of the pipe, $g\cos(\alpha)$, leads to the aforementioned split spiral flow patterns, and also serves to stabilize the flow. In runs with the α = 87^o inclination of the heated test section, which is close to the vertical orientation, wave-like laminar instability of the flow, with an almost sinusoidal pattern, was encountered well downstream of the inlet.

CONCLUSION

In this paper, an experimental apparatus and procedures for visualization of mixed convection flows in vertical, horizontal, and inclined pipes subjected to a uniform wall heat flux were presented and discussed. In the proposed apparatus, a thin, electrically conductive, semitransparent gold-film heater was suitably attached to the outside surface of a Plexiglas pipe. This Plexiglas-pipe-gold-film-heater assembly was enclosed within a larger concentric Plexiglas tube, and air in the annular chamber between these tubes was evacuated using a vacuum pump, to achieve an essentially transparent and excellent insulation of the heated tube. The key advantage of the proposed experimental apparatus is that it permits flow visualisation over the entire heated portion of the pipe, without needing the removal its primary insulation or compromising the imposed thermal boundary condition.

Flow visualization photographs obtained using the proposed apparatus were presented for laminar mixed convection with the heated test section in the vertical and several inclined orientations, and the working fluid (distilled water) flowing upwards, and also with the test section in the horizontal orientation. The flow patterns revealed by these photographs and related visual observations were discussed. Some of these flow patterns were qualitatively similar to the earlier numerical predictions of Bernier and Baliga (1992b), Cheng and Hong (1972), and Laouadi et al. (1994). The proposed apparatus and others that may be built using the techniques presented in this paper could serve as useful experimental tools for further studies of mixed-convection flows in pipes.

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