Survey of experimental channels employed on investigation of a non-isothermal laminar flow and design requirements for a new experiment

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Abstract. In this article, a literature survey of the experimental channels used for investigation of a non-isothermal flow is presented. Particular interest is focused on the flow stability with a heated wall by a uniform heat flux. The aim of this work is to prepare a comprehensive overview of the technical design and experimental settings used in previous studies. Collected information shall help to design and manufacture new horizontal channel with a rectangular cross-section with a width of around 200 mm and a height of 20 mm. The channel will be equipped with a constant heat flux section on a bottom wall for investigation of the vortex structures and the flow instabilities using modern optical methods. The channel will operate with liquid (most probably water) in the range of low Reynolds numbers. Parallel laminar flow with Poiseuille velocity profile at the inlet of a heated section and a uniform heat flux predefine the essential requirements on the channel design.

1 Introduction

Flow stability with a presence of a heat flux near the wall plays on one hand an important role in many technical applications, such as design of effective cooling and heating, and on the other hand represents an interesting fluid mechanics phenomena that have not been sufficiently described so far. In order to describe and predict the thermal stability under various conditions, the accurate experimental measurements still represent the most promising approach. The numerical simulations, i.e. the computational fluid dynamics (CFD), still suffer of rather significant inaccuracies when it comes to prediction of the heat fluxes and the thermal flow stability. Hence the simulations need to be verified on sample experimental examples, e.g., with a simple geometry and with well-defined both flow and thermal characteristics.

A summary of previous studies presented in this work will serve as an important inspiration in the design and construction of a new rectangular channel intended for the experimental investigation of a non-isothermal flow at low Reynolds numbers. The motivation for our long-term research is to obtain new accurate experimental data for a non-isothermal flow by detecting a transition from a laminar pure forced convection, to a laminar mixed convection, and finally to a fully turbulent unsteady mode. The new data would help to better describe the character of the non-isothermal flow with a constant heat flux and could possibly be employed on the verification of numerical simulations.

2 Review of non-isothermal rectangular channels

2.1 Water channels

Osborne and Incropera [1] studied water flow in a rectangular duct heated from the bottom and the top. Sidewalls of the test section were made of 12.7 mm plexiglass plates. The top and bottom walls consisted of 9 mm thick aluminium sheet to which a heater and a thermal insulation were attached. The channel consisted of an inlet developing section, a heated test section, and a tail section avoiding possible negative effects of flow structures at the channel output. After the tail section, the water flew through a system of pipes into the tank with a coil maintaining the temperature of the circulating water. The tank was connected to a return loop with a pump, a valve, and a flowmeter system, which returned the flowing water back to the duct inlet section equipped with a flow straightener. A simplified scheme of the water circuit together with construction layers of the heated wall are shown in Fig. 1.

Maughan and Incropera [2] and Incropera et al. [3] studied the vortex structures of a mixed convection in a water flow. For this purpose, a rectangular duct heated from the bottom adapted for the flow visualization with a dye stream was used. The top and side walls of the channel were made of transparent acrylic sheets. The bottom heated wall was manufactured with a requirement for a uniform heat flux. Its layers are schematically described in Fig. 2.

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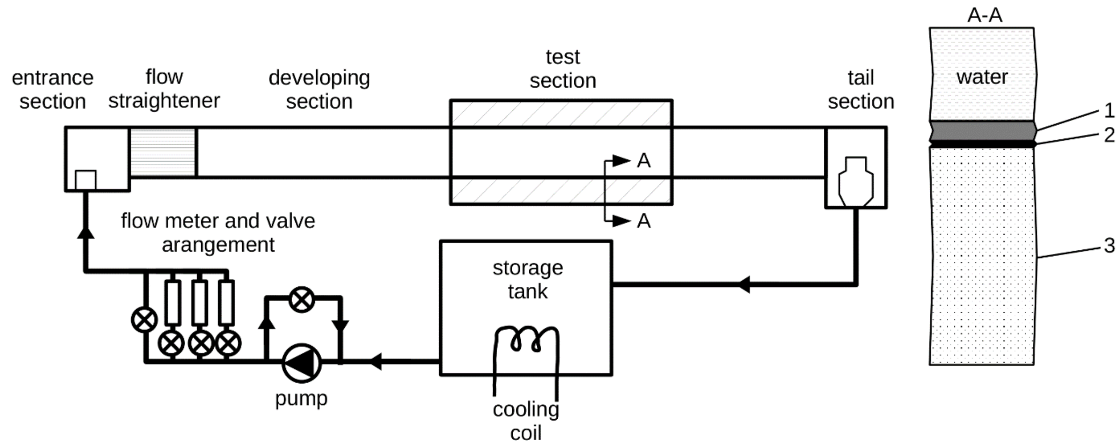

Fig. 1. Scheme of Osborne's water circuit. *1* aluminium sheet, *2* resistance heater, *3* thermal insulation.

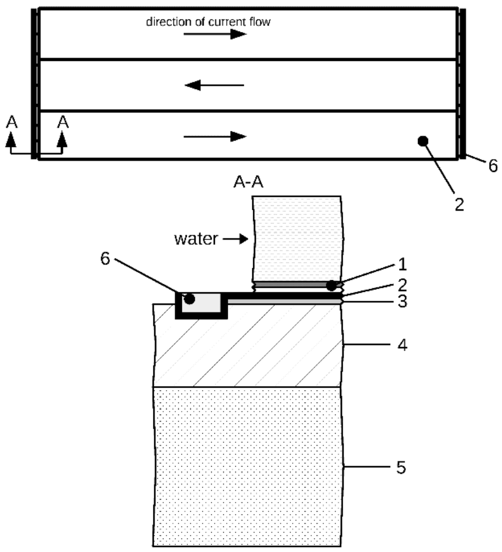

Fig. 2. Scheme of layers of heating segment of Maughan and Incropera experiment. *1* Mylar/adhesive composite, *2* steel foil, *3* transfer tape, *4* plexiglass substrate, *5* Styrofoam insulation, *6* copper bus.

The heating element was realized by three strips of 0.05 mm thin stainless-steel strips oriented longitudinally side by side with 1 mm wide gaps. At the end, the stainless-steel strips were connected in series to the copper buses. On the inner side, the layer with steel strips was covered with a 0.13 mm thick mylar/adhesive composite. It was applied to layers of adhesive transfer tape (0.05 mm), plexiglass substrate (12.7 mm) and polystyrene thermal insulation (50.8 mm). The temperature conditions at the bottom part of the channel were examined using liquid crystal sheets. A negligible overheating in the bus area and a minimum effect of 1 mm gaps between the stainless-steel strips were indicated. The thermocouples for measuring the wall temperature were placed on the outer side of the steel foil. They were attached using a thermal conductive epoxy. The original water circuit by Osborne and Incropera [1] shown in Fig. 1 was used. However, the test section was placed right after the flow straightener.

Another experiment for an investigation of the thermal stability in a water flow was carried out by Benderradji et al. [4]. The rectangular channel consisted of a developing, test and an end section as shown in Fig. 3. The test section was also made up of several layers. The heated bottom consisted of transparent polycarbonate (10 mm), three electric heaters and copper sheet (2 mm). Upper and lateral walls were made of 10 mm plexiglass. The channel was adapted for dye visualization again. Except for the water tanks, the power supply, the flowmeter and the valves for setting the desired flow rate, the experiment was placed on a table with a vibration control system.

A rectangular water channel by Koffi et al. [5] created to study the flow influenced by side-wall heating is depicted in Fig. 4. The experimental section was constructed of 3 mm plexiglass and the heated section was realized by strata made of a copper sheet, strip electrical resistor and thermal insulation. The experiment was adjusted for measurement with PIV (Particle Image Velocimetry) and the temperature was recorded by infrared camera.

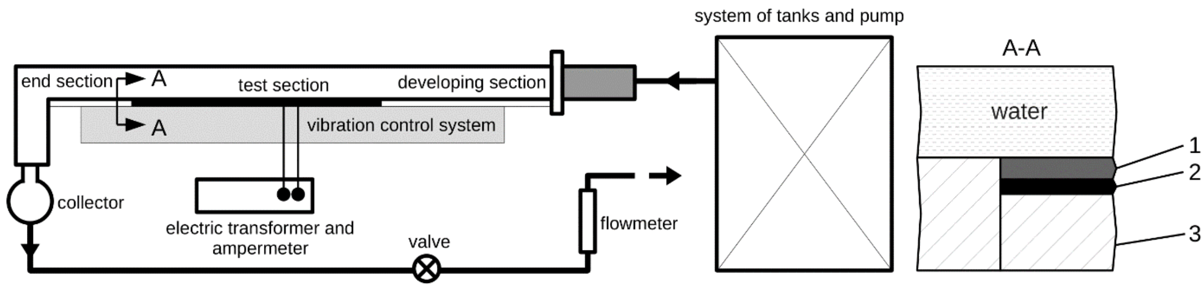

Fig. 3. Scheme of water circuit by Benderradji et al. *1* copper sheet, *2* heater, *3* transparent polycarbonate.

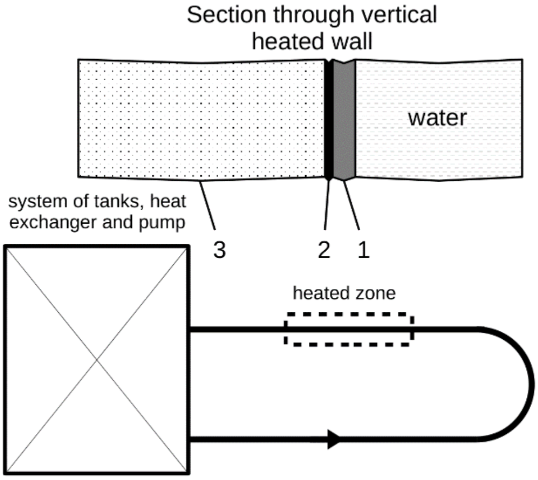

Fig. 4. Scheme of the water circuit by Koffi et al. *1* copper sheet, *2* strip electrical resistor, *3* thermal insulation..

2.2 Air channels

The experimental channels described in this section were designed to study non-isothermal air flow. The first is the channel by Hwang et al. [6], which allowed to vary a channel height and to investigate influence on the flowing structures. The test section is shown in Fig. 5. The bottom wall was made of 0.5 mm thick polished and black lacquered aluminium sheet. The heater was made of 0.65 mm Ni-Cr resistance wire wrapped around a 5 mm thick asbestos plate. A 20 mm asbestos plate was placed from the outside as the thermal insulation. The heating section was divided into three segments in the main flow direction and they were controlled individually by a voltage regulator. The top and side walls were made of 6 mm plexiglass.

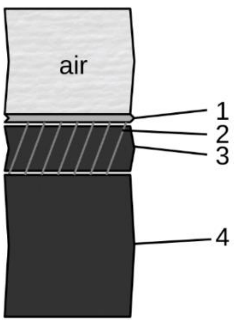

Fig. 5. Scheme of heating wall layers in the channel by of Hwang et al. *1* polished and black lacquered aluminium sheet, *2* Ni-Cr resistance wire, *3* asbestos plate, *4* asbestos thermal insulation.

In 2006, Chen et al. published [7] a study about the effect of a solid prism insertion on various channel position to explore the possible stabilization of the vortex flow. The 15 mm copper bottom wall was electrically heated by a DC power supply and the 3 mm glass upper wall was cooled by water which was running through a 3 mm gap between the glass wall and a 2 mm plexiglass plate, as shown in Fig. 6. The channel was braced up with a copper alloy frame.

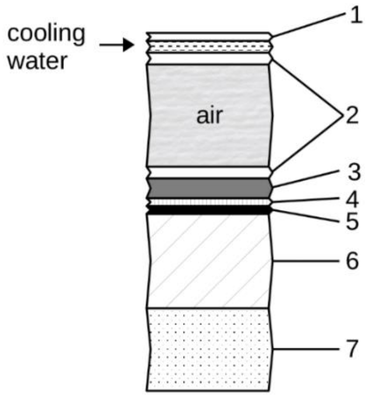

Fig. 6. Scheme of layers of Chen et al. heating bottom wall and cooling top wall. *1* plexiglass plate, *2* glass plate, *3* copper sheet, *4* mica sheet, *5* heater, *6* bakelite, *7* thermal insulation

Mergui et al. [8] studied the influence of the channel width, therefore the channel allowing lateral movement of the sidewalls was used. The heated bottom wall was realized with 10 mm copper sheet and independent heaters. Other walls were made of 5 mm polycarbonate. The upper wall was cooled by a water loop because of an extension of experiment conditions (upper cooling causes the same effect on the longitudinal roll structures as lower heating). Scheme of the heated wall is depicted in Fig. 7.

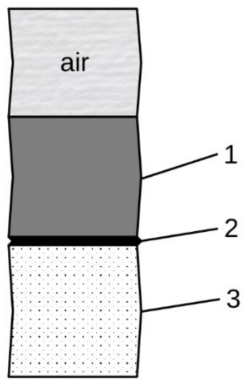

Fig. 7. Scheme of layers of Mergui's heating wall. *1* copper sheet, *2* heater, *3* thermal insulation.

3 Water channel developed for preliminary experiments

Within the frame of the master's degree thesis of A. Žemličková [9] defended at the Department of Power Engineering Equipment of the Technical University of Liberec, a water channel schematically shown in Fig. 8 was recently designed and manufactured. The channel was made of 10 mm thick glass sheets and was intended for preliminary measurements of a non-isothermal water flow. Unfortunately, the channel was found to suffer of several construction problems which precluded measurement of accurate data that could be used, for example, for reliable verification of the numerical simulations. The problematic design issues can be summarized as follows:

- The heating foil was attached externally on an outer side of the channel. Due to the low thermal conductivity of the glass, a poorly defined heat transfer to the flowing water could be achieved.
- Channel walls were joined in a way that approximately 1 mm thick layer of glue appeared in the inner corners of the channel, which did not allow to observe the boundary layer in the immediate vicinity of the heated bottom wall.
- The construction allowed only limited access to internal surfaces of the channel necessary for the channel maintenance and cleaning.
- The channel construction was not sufficiently stiff for the safe manipulation.

We note that it is not a scope of this work to discuss results obtained with this channel. For more details, please see ref. [9]. Only the construction aspects are discussed here.

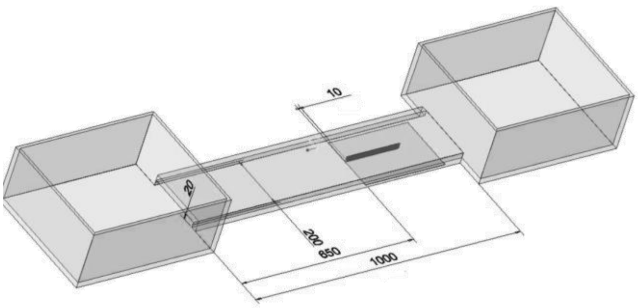

Fig. 8. Model of channel for initial experiments [9]

4 Requirements on channel construction

Based on the literature survey and own experience with the water channel described in section 3, the design of a new water channel shall take into account following requirements:

a) sufficiently long developing and exit sections for a fully-developed laminar Poiseuille velocity profile at the beginning of the heated test section,
b) inner surfaces without disturbing edges or steps between individual sections and sufficiently smooth polished inner surfaces,
c) uniform and well-defined heat flux at the bottom of the heated segment,
d) elimination of hardly measurable heat losses into the channel construction and ambient, i.e. installation of a duct insulation, especially at the channel lower part,
e) enough thermal conductivity of the bottom wall in order to maximize the heat transfer into the flowing liquid,
f) avoid heat conduction before and after the heated section. A possible solution could be an installation of a secondary water circuit for cooling the lower part of the channel before and after the heated test section. A secondary circuit could be probably designed as an additional loop of the main circuit in order to maintain the same temperature as inside the main channel.
g) simple maintenance and cleaning of the test section, ideally the possibility of opening the top wall of the channel,
h) perpendicular joining of walls without a corner glued joint that would obstruct the view of the boundary layer,
i) continuous regulation of the flow rate and the heat flux,
j) transparent side and top walls to allow for precise visualization,
k) sufficiently large water tanks before and after the channel to achieve approximately constant temperature of the circulating water and to limit possible flow fluctuations caused by the pump,
l) support platform for transversal and longitudinal manipulation of the channel for scanning by cameras across the experimental section,
m) compact dimensions due to space limitations in the laboratory and an optical table length of around 1500 mm,
n) channel support frame probably made of aluminium profiles ensuring stiffness of the whole apparatus and allowing its safe mobility.

5 Conclusion

A review of the technical design of water and air channels intended for investigation of a non-isothermal flow with a constant heat flux on a boundary wall was prepared. The technical solution of the necessary elements such as the wall heating or cooling were described. Based on the previous works of other researcher and on own experience acquired with a preliminary water channel made of glass, a set of important requirements on the design of a new water channel was defined.

The new channel shall allow to collect data for the non-isothermal flow over a heated surface. At present, preparatory calculations and construction works necessary for the channel design are undertaken.

Acknowledgment

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