EXPERIMENTAL EVALUATION OF NATURAL CIRCULATION PRESSURE DROP IN A BOILING CHANNEL

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I. INTRODUCTION

Natural circulation systems have many applications in nuclear industry because of their advantages such as elimination of pumps, better flow distribution, safety aspects and simplicity. Some of these applications are containment cooling, reactor building ventilation, cooling of radioactive waste storage facilities and natural circulation based steam generators in PWR, PHWR and VVER. Natural circulation systems are extensively used in shutdown heat removal and post accident heat removal. Almost all designs of nuclear power reactors are designed to remove decay heat by natural circulation in the event of a complete loss of pumping power (CLOP). A few small sized nuclear power reactors like Humbholdt Bay, Dodewaard and VK-50 demonstrated successfully the feasibility of operation with natural circulation as the normal mode of core cooling. Today natural circulation is beginning to be seriously considered for cooling of core under normal operating conditions [1].

A joint project among three Agencies: the International Energy Agency (IEA), the OECD Nuclear Energy Agency (NEA), and the International Atomic Energy Agency (IAEA) prepared the report "Innovative nuclear reactor development, opportunities for International cooperation" [2], whose main objective is the identification of opportunities to establish joint projects in developing nuclear fission reactor technologies. This study remarks that the following areas are good candidates for developing new, broad based collaborative efforts: 1.natural circulation; 2.high-temperature materials; 3.passive (safety) devices; 4.in-service inspection and maintenance methods; 5.advanced monitoring and control technologies; 6.delivery and construction methods; 7.safeguard technologies and approaches [3].

Large scale deployment of Natural Circulation based reactors and safety systems depend on the successful resolution of the challenges specific to natural circulation which are driving force, pressure drops, instabilities, start-up and operating procedure, and critical heat flux [1]. In this work, natural circulation two-phase flow pressure drops in a single channel are studied experimentally. For this purpose, natural circulation hydrodynamic loop was designed. The overall pressure drop was measured by use of pressure transducer sensors and the void fraction in visible boxes which located at the end of heated tube is measured by use of high speed camera. The frictional and acceleration pressure drop are evaluated in different conditions from experimental data and corresponding theoretical formulas.

II. SHIRAZ UNIVERSITY NATURAL CIRCULATION LOOP

Shiraz University Natural Circulation Loop (SHUNCL) is an experimental test facility which was designed in Shiraz University to study natural circulation phenomenon. Evaluation of the driving force and pressure drops, studying instabilities, and other related challenges of using natural circulation are the purposes of SHUNCL experiments. The subject of this paper is related to pressure drops studies. The main characteristics of SHUNCL are presented here.

II.A. General Characteristics of SHUNCL

The main components of the test loop are a downcomer carrying the downward flow from the vessel to the heat source, heated section where the working fluid, which is water in this study, gets heat, and a pressure vessel. SHUNCL test facility is shown in Fig.1. Three visible boxes are located in different position of heated section for high speed camera photographing. The capacity of the vessel is 225liters and the overall height of the loop is about 10meters.

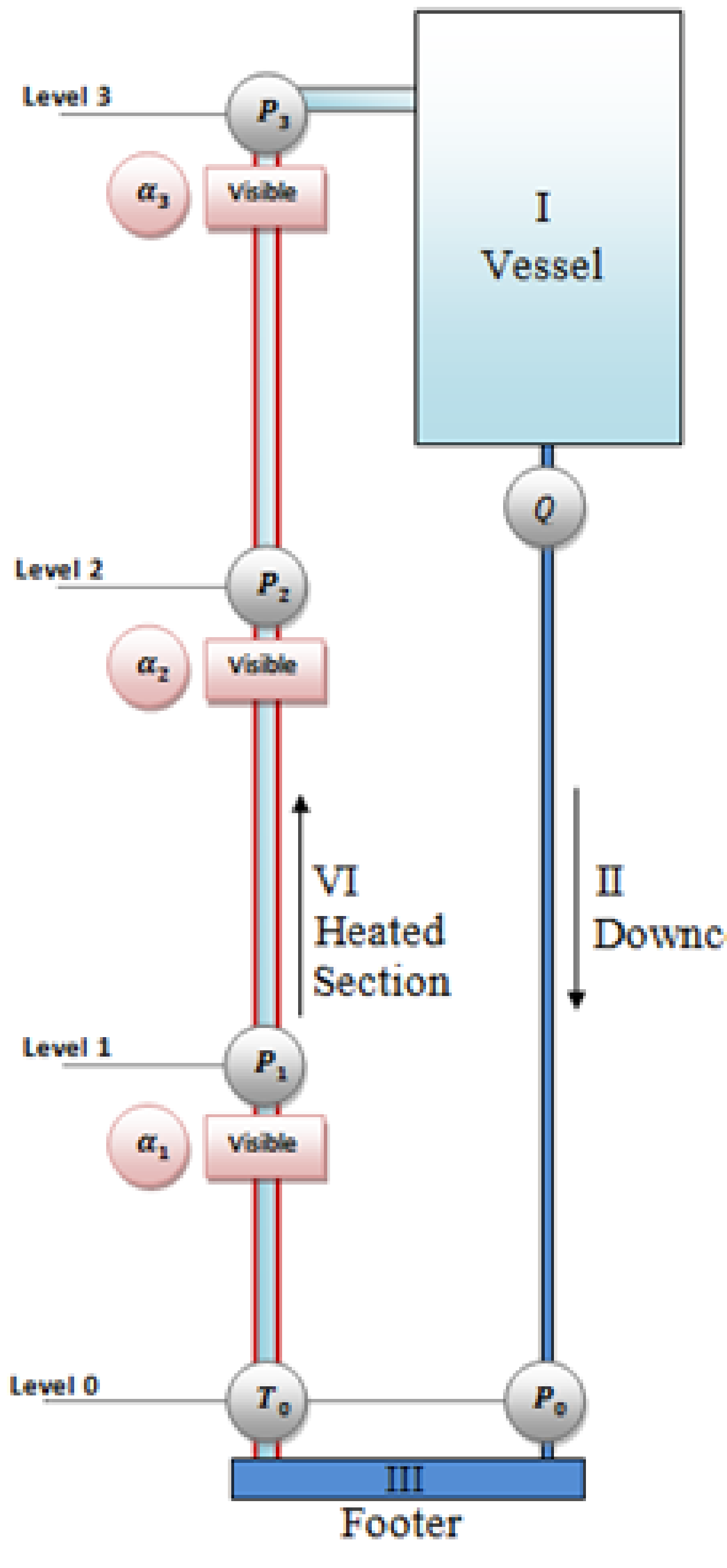

Fig. 1. The schematic of SHUNCL.

The diameter of the downcomer and heated section of the test facility are changeable to study the effects of these parameters on the flow rates and other characteristics of natural circulation. There is footer in the bottom of the loop which connects the downcomer and heated section. There is an expansion joint at the end of the heated section to compensate the expansions of the pipes due to change in temperature. The heated section contains electrical heating elements around pipe. By control of these heating elements, different linear power densities, heated section and chimney heights are available. The characteristics of SHUNCL are summarized in Table I.

In this study, the pressure of the vessel remains atmospheric and the diameters of the downcomer and heated section are 1.5 and 2inches, respectively. The linear power density at the steady state condition was 2kW/m and the height of heated section was 8meters.

TABLE I. The characteristics of SHUNCL

Pressure Vessel Capacity	Linear Power Densities	Max. Pressure	Heated Section Heights	Chimney Heights
225 (Liters)	1, 2, 3, 4 (kW/m)	10 (bar)	2, 5, 8 (m)	3, 6 (m)

II.B. Experimental Measurements

Different parameters such as flow rate, temperatures, and pressures in the different positions of SHUNCL were measured by use of different instruments. These parameters were used to study natural circulation phenomenon in the loop in the different operating condition. The operating conditions which are concerned in this study are atmospheric pressure of the vessel, linear power density of 2kW/m in the 8meters heated section.

The main parameters which are measured and are used in this study are as follows. Two different temperature sensors were used to measure temperature of the working fluid at the entrance of the heated section and at the end of it. Also the pressure of the working fluid at the entrance of the heated section and at the end of it, were measured by use of two pressure transducer. Two different ultrasonic flow meters were used to measure the flow rate of the downcomer. In the case of two phase flow, the void fraction, the slip ratio, and the flow patterns were evaluated by processing of the images from high speed photography of the flow via the visible boxes. Fig.2. shows one of the visible boxes of SHUCNL. The results of these measurements and discussion about them are presented in the next section.

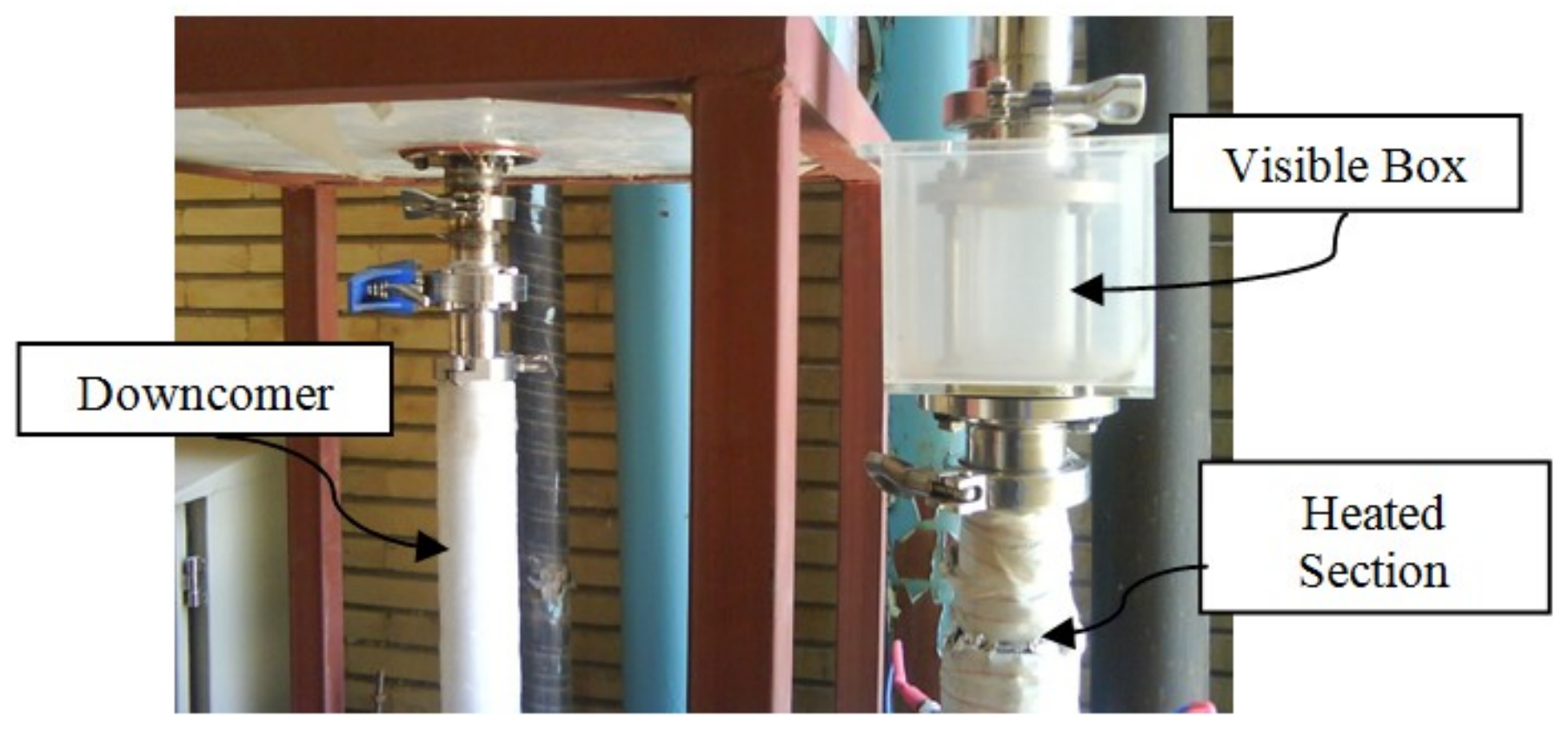

Fig. 2. SHUNCL visible box for high speed photography

III. RESULTS AND DISCUSSION

The flow rate and the total pressure drop of working fluid in the heated section were measured experimentally. The results of these measurements and discussion about them are presented here.

III.A. FLOW RATE BEHAVIOR

The flow rate of the working fluid starts to increase during a few seconds after turning on the heating elements. This is because of the change in density of fluid in the heated section in comparison with downcomer and corresponding driving force. This increasing is slow in the single phase region as shown in Fig.3.

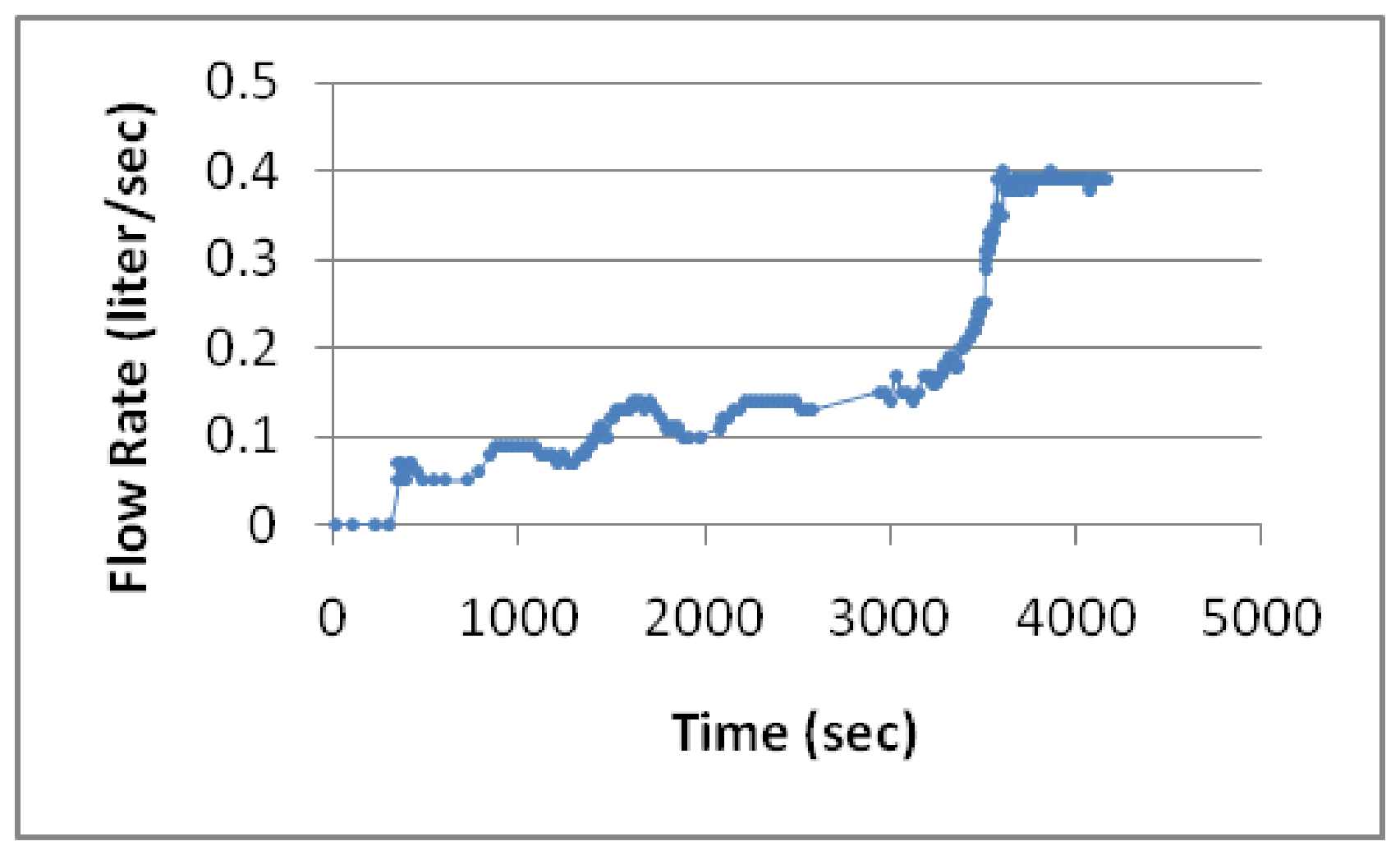

Fig. 3. Experimental flow rate of SHUNCL

As it expected, there is a suddenly change in the increasing rate of flow which is due to change in phase. The flow rate increases as the void fraction increasing. The flow rate reaches the constant value at the steady state condition which is 0.4liter per seconds for 2kW/m linear power density.

III.B. PRESSURE DROPS

The experimental pressure drop of SHUNCL which were measured across the heated section by use of pressure transducer is presented in Fig.4.

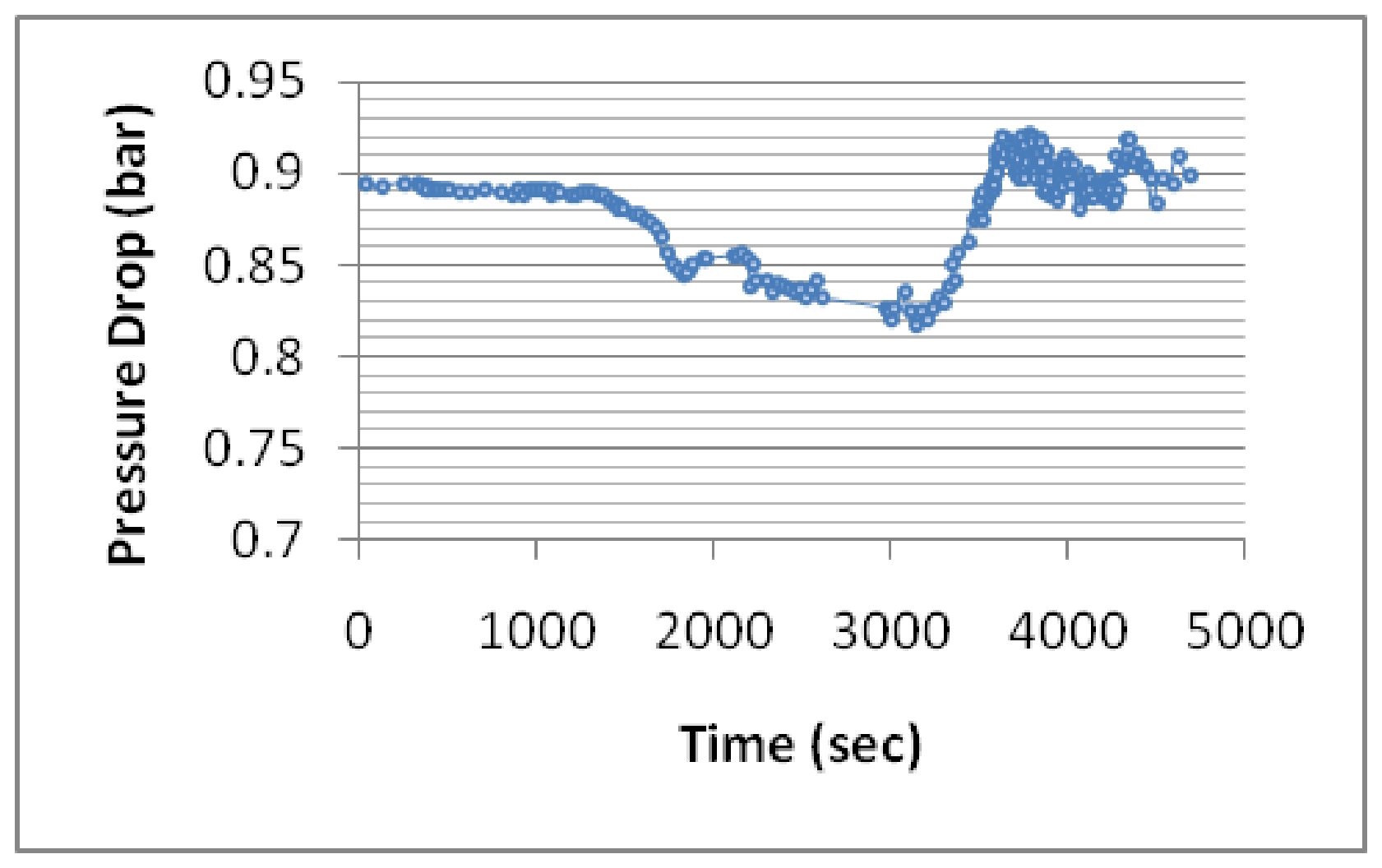

Fig. 4. Total pressure drop across heated section

The pressure drop of SHUNCL in the heated section consists of three different terms. These terms are frictional pressure drop, gravitational pressure drop, and acceleration pressure drop in the equation (1). The last term is due to change in momentum of fluid in the entrance of pipe and at the end of it. This term is more serious in the case of two phase flow [4].

$$\Sigma\Delta P = \Sigma\Delta P_f + \Sigma\Delta P_g + \Sigma\Delta P_a \qquad (1)$$

During startup condition there is a decreasing in pressure drop which is because of change in density and its effect on gravitational pressure drop term. After this decreasing, there is an increasing in pressure drop when boiling starts. This is because of effect of acceleration pressure drop which is more serious in the case of two phase flow.

The pressure transducer in the SHUNCL measured the total pressure drop. The acceleration pressure drop could be calculated by use of equation (2) for single phase flow and equation (3) for two phase flow [5].

$$(\Delta P_a)_{SP} = G^2\left(\left(\frac{1}{\rho_f}\right)_2 - \left(\frac{1}{\rho_f}\right)_1\right) \qquad (2)$$

$$(\Delta P_a)_{TP} = G^2\left(\left(\frac{(1-x_e)^2}{(1-\alpha_e)\rho_f} + \frac{x_e{}^2}{\alpha_e\rho_g}\right)_2 - \left(\frac{(1-x_e)^2}{(1-\alpha_e)\rho_f} + \frac{x_e{}^2}{\alpha_e\rho_g}\right)_1\right) \qquad (3)$$

Where G is mass flow rate (kg/m^2s), x_e is exit quality and α_e is exit void fraction. Thermo physical properties of working fluid were used from references [6] and [7].

The gravitational pressure drop could be calculated by use of equation (4) for single phase flow and equation (5) for two phase flow [5].

$$(\Delta P_g)_{SP} = \bar{\rho} g \Delta Z \qquad (4)$$

$$(\Delta P_g)_{TP} = \left(\alpha_e\rho_g + (1-\alpha_e)\rho_f\right) g \Delta Z \qquad (5)$$

Therefore the frictional pressure drop could be calculated from equation (6).

$$\Delta P_f = \Delta P_{measured} - \Delta P_g - \Delta P_a \qquad (6)$$

To calculate the gravitational and the acceleration pressure drop from corresponding formulas, evaluation of the exit void fraction is necessary. For this purpose visible boxes were designed in SHUNCL. The high speed camera was used to capture the image of flow patterns across these visible boxes. The void fractions were evaluated by processing of these images. For instance, two frames of these images are shown in Fig.5. The camera mode in these images was 500 frames per seconds.

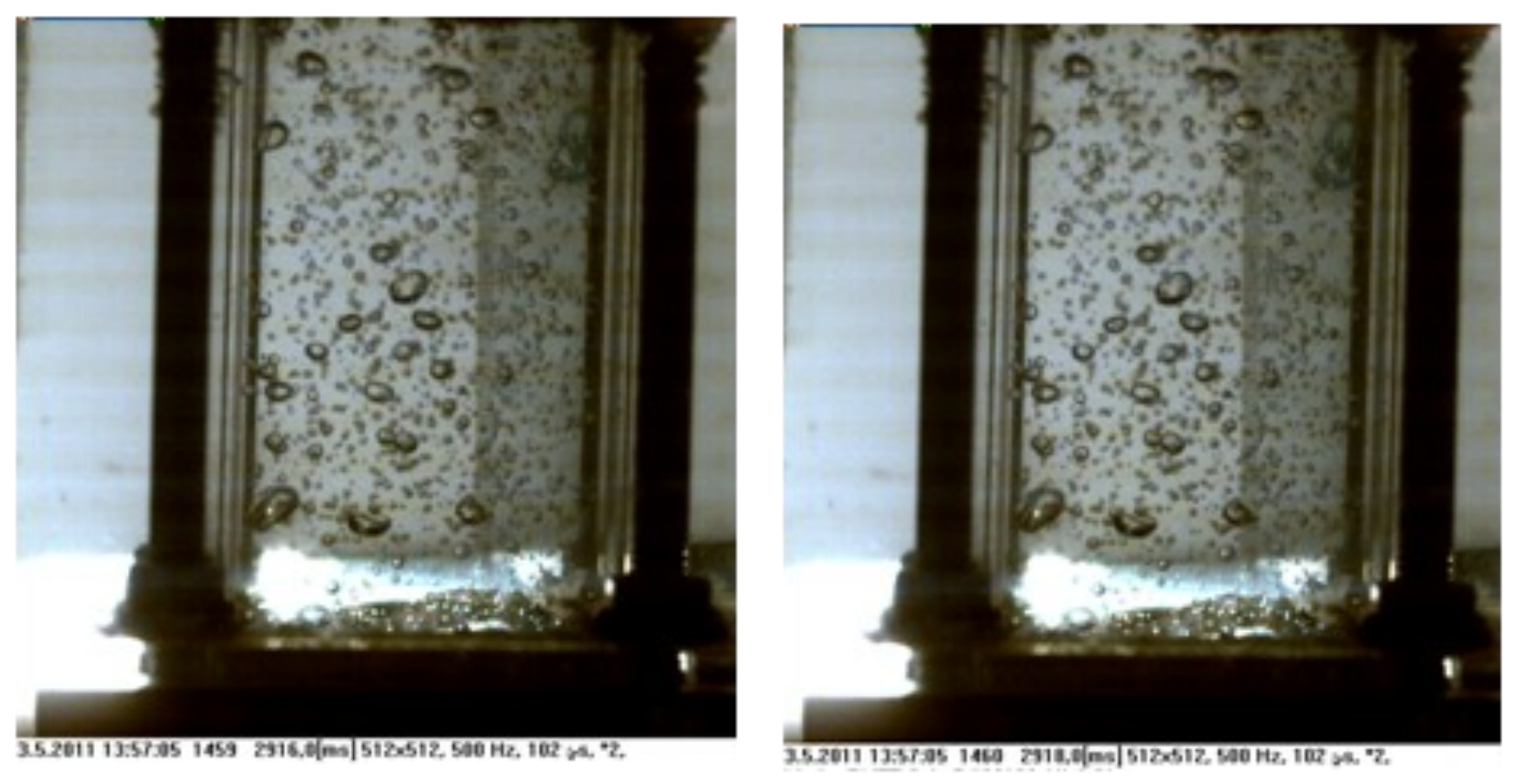

Fig. 5. Two consequent frames of high speed camera photographs in mode of 500 frames per second

Fig.6. shows different components of pressure drops of heated section at the steady state condition. The black line is corresponding to total pressure drop. The green line is corresponding to frictional pressure drop. The red line is corresponding to gravitational pressure drop, and the blue one is corresponding to acceleration pressure drop.

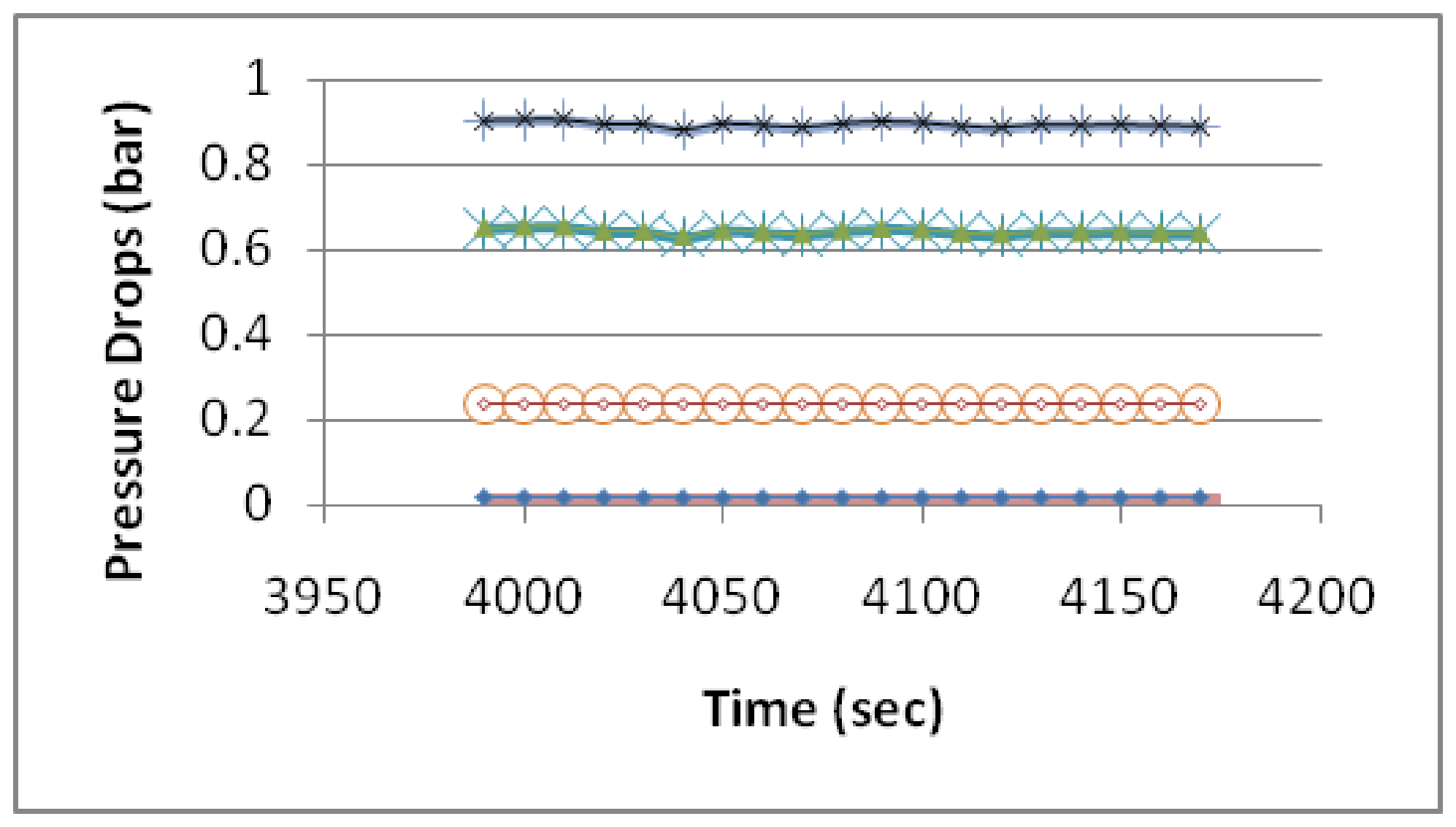

Fig. 6. Total pressure drop and its component during steady state condition

IV. CONCLUSIONS

In this work, natural circulation two-phase flow pressure drops in a single channel are studied experimentally. For this purpose, natural circulation hydrodynamic loop was designed. The flow rate was measured in the single phase region and two phase region. The flow rate reaches the constant value at the steady state condition which is 0.4liter per seconds for 2kW/m linear power density.

The overall pressure drop was measured by use of pressure transducer sensors and the void fraction in visible boxes which located at the end of heated tube is measured by use of high speed camera. The pressure drop decreases in the single region with increasing in temperature. It is because of effect of density on gravitational pressure drop. The pressure drop starts to increase when boiling occurs in the heated section. It is because of effect of acceleration pressure drop which is serious in the two phase region. The gravitational, acceleration, and frictional pressure drops were evaluated in different conditions from experimental data and corresponding theoretical formulas.

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