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## Digital Flow Rate Measurement System Design for Minichannel based on Cross Correlation Technique

**Abstract-** In this paper, a demonstration for an experimental study to measure mean fluid velocity in minichannels is presented. Fluid flow velocity was estimated by applying cross correlation technique on measured thermal fluctuation using two ultra-small thermistors in every channel. These experiments were conducted on two flow field plates (single serpentine and parallel Z-type arrangement) with dimensions ( $L*W*H=75*70*3\text{ mm}^3$ ,  $W_c=3\text{ mm}$ ,  $H_c=1\text{ mm}$ ,  $W_r=4\text{ mm}$ ,  $W_h=3\text{ mm}$ ,  $H_h=1\text{ mm}$  and  $N=8$  for parallel Z-type) with various values of Reynolds number ( $Re=70,100,120,150,175$  and  $200$ ). A special experimental setup was erected for purpose of conducting the experiments, sensors output was delivered to a data acquisition system working under LABVIEW program which was used to collect data and perform cross correlation operation on the recorded output signals taken from the two temperature sensors residing in every channel. This new technique for measuring mean velocity in a minichannel proved to be in good agreement with results obtained from previous theoretical studies.

**Keywords-** Cross Correlation; Minichannel; Flow Rate Measurement; LabVIEW.

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**1. Introduction**

Nowadays many research and dissertations consider the flow rate measurement system as a main topic of great interest due to their evolutionary application in the industrial world. It is also one of the most difficult jobs because the medium being measured can take place in a variety of physical states. The choice of measurement method is further complicated by the specific requirements of the measurement process, which involves the measuring range, minimum loss of pressure, minimum possible resolution, and continuous or non-continuous monitoring [1]. Several proposed flow measurement techniques have been developed to suit the increasingly varying environments where a certain fluid flow rate or speed is required to be measured such as [2-4]. The main cores of the motivation for measuring the velocity distribution in minichannel for this work are [5-8] because the basic problems in flow or velocity measurement in the minichannel system are still there waiting to be addressed, therefore; the fundamental essence of the contributions of this paper is the thermal flow measuring with cross correlation technique that heat up the fluid to such a temperature that the fluid may ignite with an acceptable accuracy, safety as well as a rather wide range of applications and to overcome the measuring flow parameters indirectly that uses electrical conductivity or capacitance which makes the specific type of the fluid measurement system,

which strongly limits the range of applications. The rest of the paper is established as follows: Section two includes description of the proposed methodology. Section three, involves details on the measurement system. The experimental results are described in section four and finally the conclusions are drawn in section five.

**Nomenclature**

C: Capacitance (F)  
d: Distance (mm)  
Hc: Channel depth (mm)  
Hh: Header depth (mm)  
Hp: Plate depth (mm)  
Lp: Length of plate (mm)  
N: Number of channel  
R: Resistance ( $\Omega$ )  
Re: Reynolds number  
 $R_{xy}$ : Cross correlation function  
T: Time period (sec)  
u: Velocity of flow (m/s)  
V: Mean velocity (m/s)  
Wp: Plate width (mm)  
Wc: Channel width (mm)  
Wr: Rib width (mm)  
Wh: Header width (mm)  
*Greek Symbols*  
 $\tau$ : Delay (lag) time (msec)  
*Superscripts*

**Design Methodology**

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In this work, the flow measurement system is based on the proposed methodology for measuring velocity that uses the cross correlation of two temperature profiles taken from two temperature sensors separated by a distance  $d$ , situated in the direction in which a stream of the fluid flows, to determine a flow's velocity. The cross correlation velocimetry technique is conceptually based on the "frozen eddy" notion in turbulent flows proposed by Taylor in 1938 [9]. The key points of the suggested scheme are presented here. Figure 1 shows a hypothetical temperature profile obtained from two temperature sensors that are spaced  $d$  (cm) apart. Since  $d$  is small, the two temperature sensors would detect the same thermal variation pattern. However, the time record for the thermal fluctuation in the flowing gas picked up by the temperature sensor located downstream is displaced by a period of  $\tau$  seconds (time lag) as shown in Figure (1). If  $\tau$  can be estimated accurately, then flow velocity "u" can be easily calculated from Eq. (1):

$$u = \frac{d}{\tau} \tag{1}$$

Where  $d$  is the thermistor separation distance in the direction of the flow and  $\tau$  is the time lag (s) between the two temperature sensor signals. In order to calculate the time for a thermal eddy pattern passing between the two temperature sensors; the obtained temperature profiles are cross-correlated by means of Eq. (2):

$$R_{xy}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t - \tau)y(t)dt \tag{2}$$

Where the temperature sensor signals are symbolize by  $x(t)$  and  $y(t)$ . The delayed version of signal  $x(t)$  is the  $x(t-\tau)$ .  $T$  is the averaging time/sampling period over which the signals are cross-correlated.

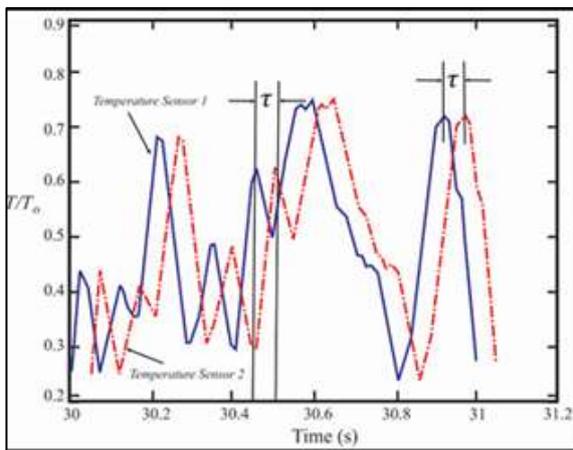


Figure 1: A hypothetical thermal fluctuation profile in a flowing fluid that is obtained from two temperatures sensors displaced by a distance ( $d$ ) inside a closed pipe

Determining the delay period  $\tau$  between the times when an eddy passes from one temperature sensor to the other demands finding the lag value that maximizes the correlation function  $R_{xy}$ .

Cross correlation velocimetry is affected by seven prime issues: the sampling frequency, the response time of the implemented temperature sensor, the distance separating the two temperature sensors, size of the thermal eddy, the accumulation of soot (if present), the closeness of time constants for the two temperature sensors, and the value of the selected sampling period. The two factors examined in this study are frequency and the distance separating the temperature sensors. The Selected value of the sampling frequency greatly influences the successful application of the cross correlation velocimetry technique because if data are not recorded fast enough the temperature changes in the thermal eddies will not be represented correctly by the temperature profiles recorded from the two temperature sensors. The feasible sampling frequency is determined by the time constant of the selected temperature sensor. Temperature sensor's time constant is the outcome of sensor's thermal inertia. Using faster sampling frequencies will merely result in longer data profiles without any increase in accuracy.

Figure 2 shows the layout of a flow measurement system based on cross correlation techniques. With the great advances in computer, technologies came huge improvements in data acquisition techniques, digital signal conditioning, and digital filtering techniques of random noise. That and the present availability of post processing statistical packages allowed for better and faster cross correlation of two random signals, therefore the technique has revived and is yielding higher accuracies and repeatability figures.

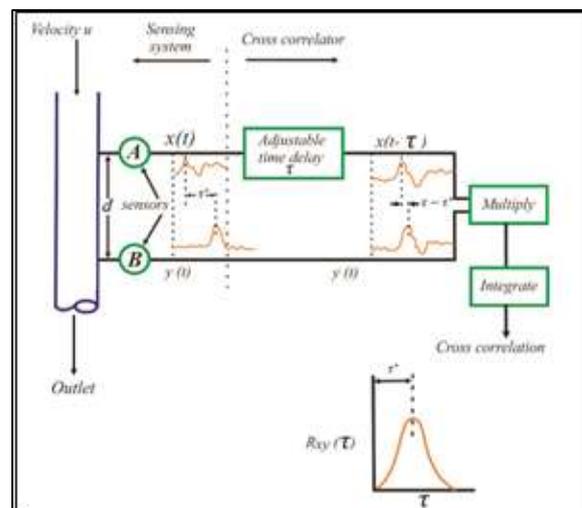


Figure 2: Cross correlation technique for fluid flow velocity

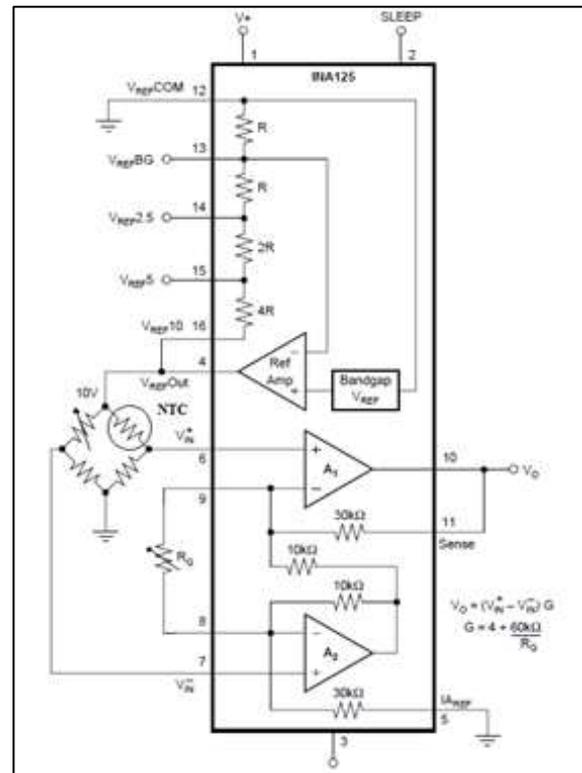
To get maximum information from the flow a need arises for sensors with minimal response time. In the designed system very small bead negative temperature coefficient thermistors the 111-103EAJ-H01 obtained from Honeywell Sensing and Control that have a diameter of 0.36 mm with very small time constant of 0.5s were used to detect thermal eddies and determining gas flow velocity using cross correlation techniques.

**2. Measurement System Description**

The measurement system setup for measuring flow velocities in the experimental minichannel modules is explained in the following lines; the sensing system consists of temperature sensing probes designed using the Honeywell “111-103EAJ-H01” micro bead negative temperature coefficient (NTC) thermistor in a temperature sensing bridge circuit designed around the Texas instruments “INA125” instrumentation amplifier which comprises a stable reference supply for the sensing bridge. Figure 3 shows the thermistor-based temperature sensing circuit elements.

The sensing bridge consists of the sensing NTC thermistor with nominal resistance of 10 kΩ at 25°C, one semi variable resistor of 10 kΩ value for bridge nulling purposes, and two fixed precisions 10 kΩ resistor. A combination of 100 Ω fixed resistor in series with a 10 kΩ semi variable resistor is used to set the instrumentation amplifier overall gain. Two of these circuits are used in each minichannels where fluid velocity is required to be measured in the cross correlation fluid velocity measurement setup. These circuits are operated from a dual 12 Volts supply. The outputs of these circuits are fed to the analogue input of the “NI 6210” data acquisition system from National Instruments.

A heating element is introduced in the flow path to generate a heat pulse; the travel of a heat pulse in the flow is the detected by the two measuring thermistors. The system functions as follows: a heat pulse is generated using a heater immersed in the flow. The heat pulse diffuses in time but is also transported by the flow and passes the two temperature sensors spaced a well-known distance apart (*d*). The flow velocity (*u*) can be obtained by measuring the delay time (*τ*). The purpose of introducing the heat pulse is to obtain a better resolution in estimating the value of (*τ*) at very low flow rates. The duration of the heat pulse generated is kept small too few tens of milliseconds so as to minimize it effect on the currently measured fluid flow. This is achieved by using a mono-stable circuit based on the μA555 timer chip which gets its trigger from one of the digital outputs of the “NI 6210” data acquisition system. The timing period can be calculated from Eq. (3):



**Figure 3: The temperature sensing circuit**

$$T = 1.1RC \text{ Sec.} \tag{3}$$

Where *T* is the period (sec), *R* is the resistance (Ω) and *C* is the capacitance (F). Figure 4 show the schematic diagram of the heat pulse generation circuit.

The “NI 6210” data acquisition system is interfaced to a laptop computer operating on modern Windows™ operating systems (Xp, Vista, 7, 8, 8.1, 10) through the USB interface. The LabVIEW™ version 14 SP1 software package controls the operation of the data acquisition system and performs all the signal processing functions like the filtering and the cross correlation function in addition to logging and presenting the obtained results. Figure 5 depicts the schematic of experimental setup that built for purpose of conducting experiments, in order to test the flow measurement system has been manufacturing flow field plates such as (single serpentine and parallel Z-type arrangement) which having dimensions (*L\*W\*H*= 75\*70\*3 mm<sup>3</sup>, *Wc*= 3mm, *Hc*= 1mm, *Wr*= 4mm, *Wh*= 3mm, *Hh*= 1mm and *N*= 8 for parallel Z-type) as shown in Figure 6 for studying the velocity distribution in each channel for each design, while Figure 7 depicts the details of the test section. It consists of an aluminum flow field plate with minichannels on its top surface, Perspex for housing and top cover plate and gasket.

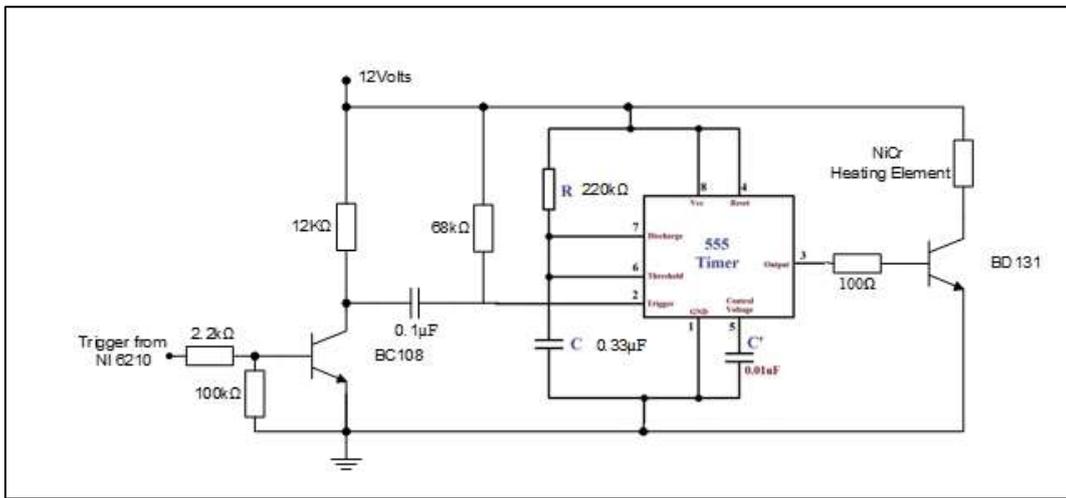


Figure 4: The pulsed heat flux generation circuit

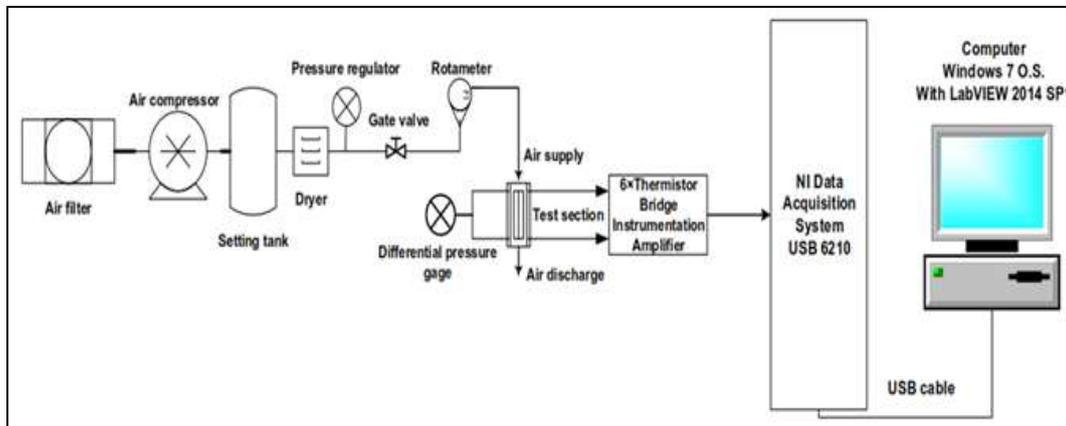


Figure 5: Schematic of experimental setup

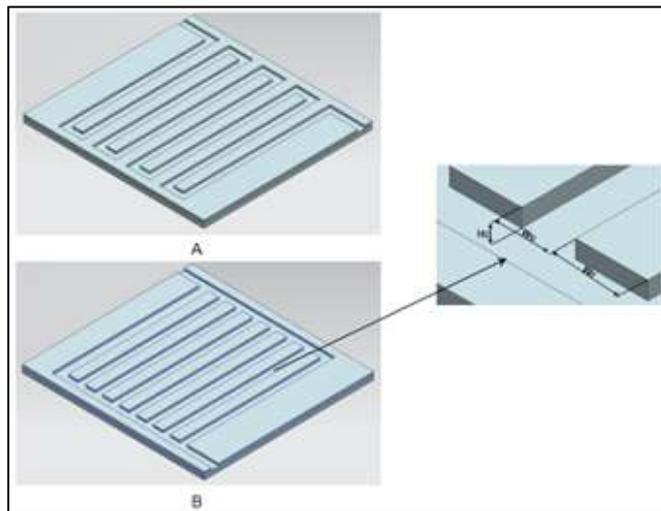


Figure 6: A and B Schematic diagram of single serpentine and parallel Z-type respectively

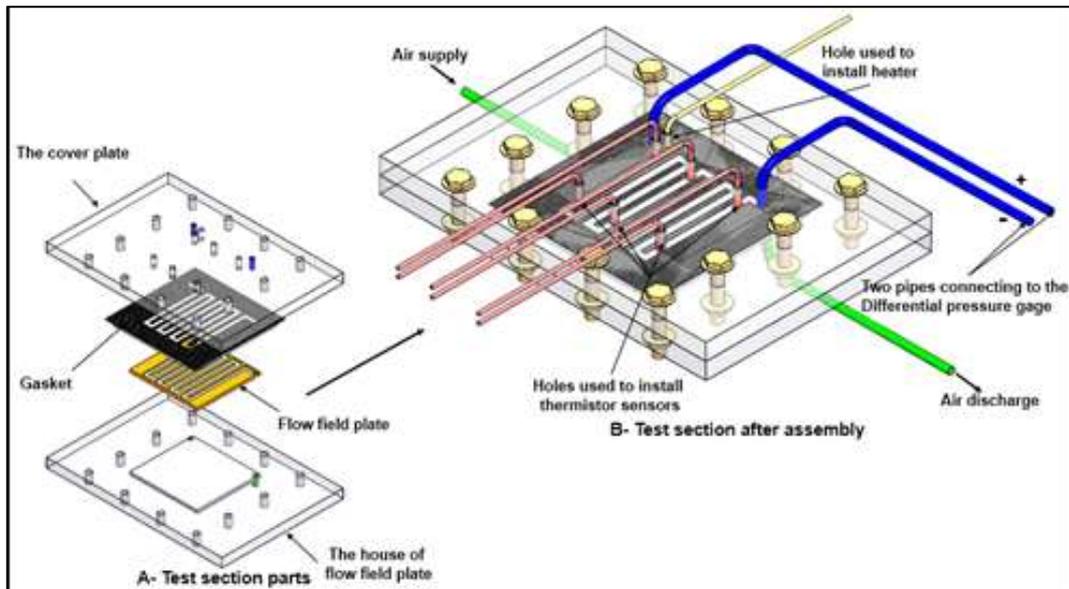


Figure 7: Schematic diagram of test section for single serpentine

### 3. Experimental Results

The fluid flow velocity measurement system explained in previous section is being employed to measure velocity of airflow in the minichannels shown in Figure 6. The LabVIEW package is put to use in this experimentation setup. It is a virtual instrument platform developed by National Instrument. LabVIEW utilizes a graphical programming language using icon code instead of text programming language therefore; it is simple, intuitive and is most widely applied in the field of automated measurement setups [10-15]. After completing the LabVIEW based program as shown in Figure 8 and selecting a sampling time of 1mSec per sample, the output of the cross-correlation function applied on the two temperature profiles obtained from the air flow over two emperature

sensors (one downstream of other) on each of the eight channels per experimentation module were processed and the resulting cross correlation functions are shown in Figure 9. These figures show samples of results that were obtained from the experimentation setup for the parallel Z-type for Reynolds number= 70. The plots observed in Figure 9 show the relation between cross correlation function (y-axis) and delay time in millisecond (x-axis). The time required for the thermal profile of fluid flow to cross the distance (d) separating the two sensors is the delay time observed on the x-axis covering the distance from zero to peak point of cross correlation function. Table 1 shows the results obtained from calculating the mean velocity in each minichannel for parallel Z-type for  $Re=70$ .

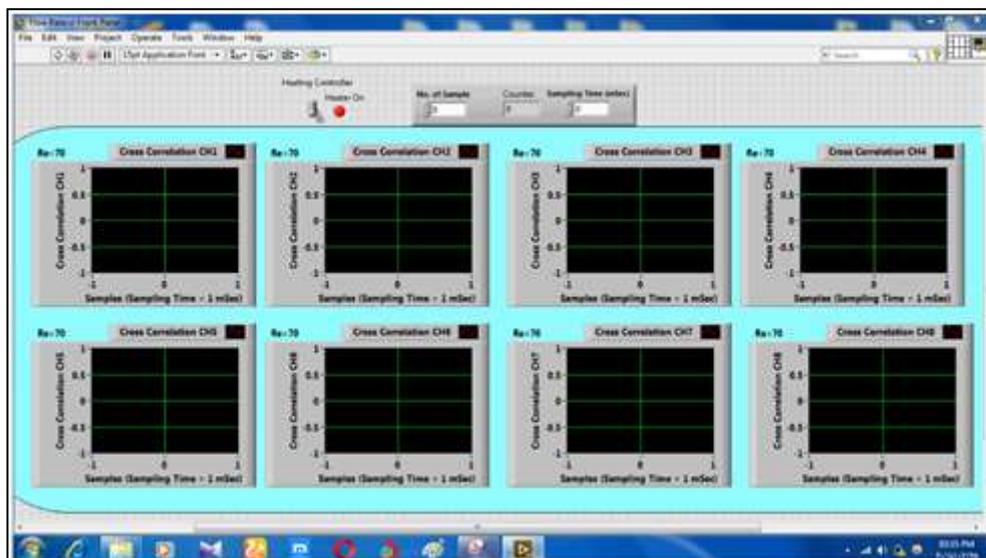


Figure 8: The LabVIEW program

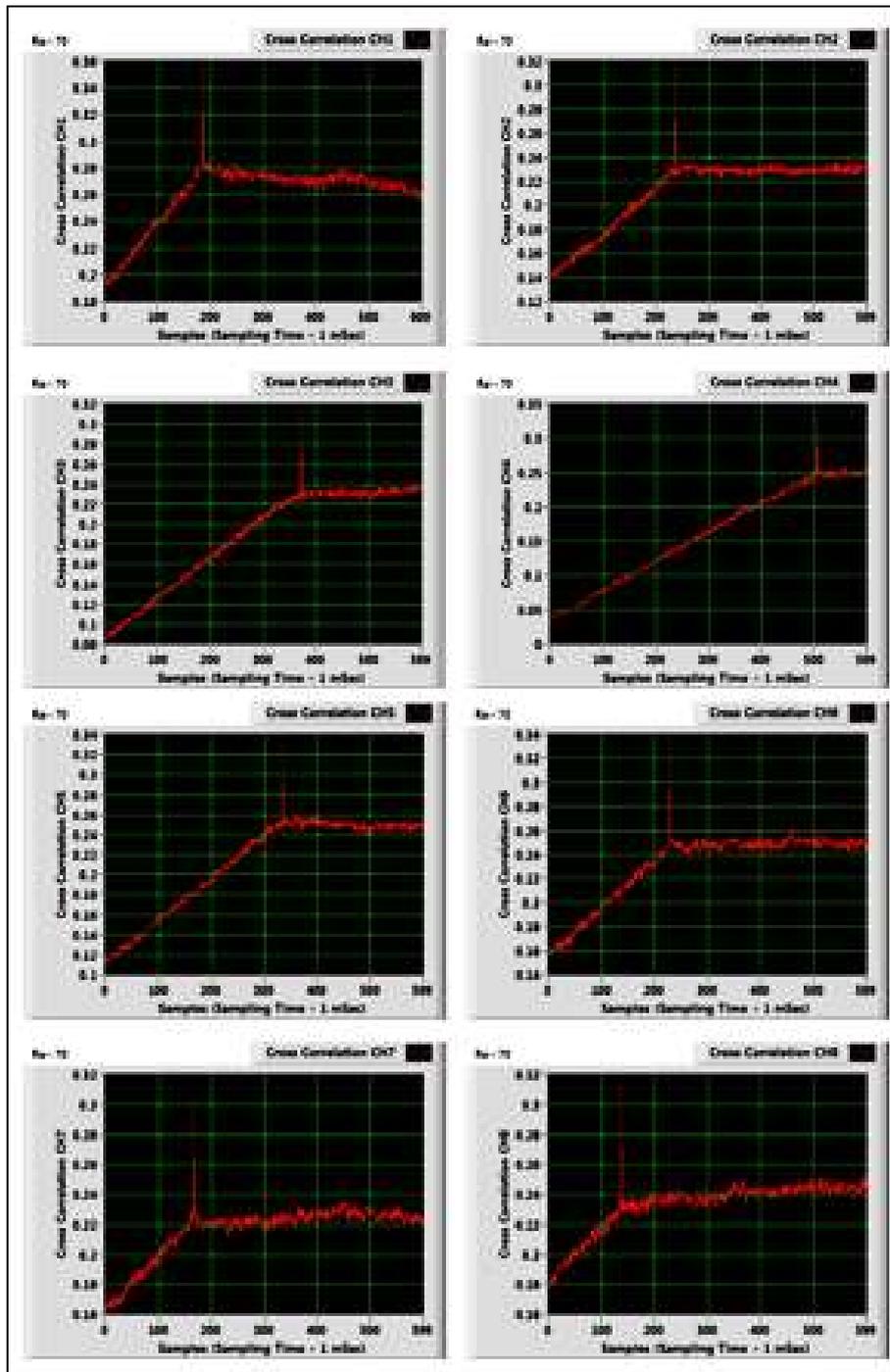


Figure 9: The cross correlation function vs. delay time for parallel Z-type

Table 1: Mean flow velocity calculated for each minichannel in the parallel Z-type

N	d (mm)	$\tau$ (msec)	V (m/sec)
1	42	186.25	0.2255
2	42	237.82	0.1766
3	42	371.35	0.1131
4	42	507.24	0.0828
5	42	334.12	0.1257
6	42	230.38	0.1823
7	42	166.27	0.2526
8	42	136.85	0.3069

Figure 10 shows the effect of Reynolds number on velocity distribution along serpentine channel. Results obtained demonstrated that the velocity distribution was nearly uniform flow along channel. This leads to uniform diffusion of reactants to reaction sites in fuel cell, this flow distribution is related to the design of single serpentine, which consists of one long channel consisting of straight sections that are interconnected at the corners where the flow is redirected. Therefore, the air is forced to flow along the channel from inlet to the outlet and that resulted in higher pressure drops due to augmented flow resistance in the longer paths detected by the increased pressure difference between the inlet and outlet of the channel. In addition, that, the acquired results demonstrated that Reynolds number increase leads to increased flow velocity along channel due to an increase in the inertial forces. Additionally, it was found that the flow velocity distribution remained nearly uniform along channel despite the increase in Reynolds number within the range of Reynolds number used throughout the conducted experiments. These experimental results were compared with theoretical study of Wang [16], it was found the experimental results were in conformity with the theoretically obtained results and illustrated the same behavior for velocity distribution along channel of this design, the reason for this was because the researcher [16] has taken into his consideration both the effect of inertia and friction in his conducted study.

Figure 11 shows the effect of Reynolds number increase on velocity distribution in each channel of the parallel Z-type arrangements. The acquired results showed that for this configuration, the last channel always received the maximum mean velocity while the minimum mean velocity was observed in the channels lying near the center because of the behavior of the static pressure which changes along intake header. This behavior occurs because of two effects: the first is the friction effect which produces a pressure drop along the header; the second is the inertial effect (the momentum of the main fluid stream going into an intake header tends to carry the fluid toward the closed end) that leads to producing a pressure rise at the closed end. This means that the maximum pressure occurs in the first and last channel therefore, these channels take higher velocity. The reason for this is due to the shape of the distribution channel in Z-type arrangement. The exhaust header has a significant effect on the flow distribution in the intake header because of the location at which air is discharged exists near the exit channel [16-19].

Looking at Figure 11, it can be observed that the increase in Reynolds number leads to increase in distribution velocity at each channel; also an increase in the non-uniformity of flow distribution in each channel has been attributed to increasing inertial forces. Additionally, it was found that the minimum velocity at the distribution channel shifts towards the first channel due to an increase in the effect of inertia (increase the momentum effect).

When comparing the experimental results with the theoretical ones obtained from the study carried out in reference [16,19], it was discovered that the same behavior of velocity distribution conformed with the work of Wang [19] and Wang [16] as they both have taken the effect of inertia and friction in their study, while comparing the results with those obtained by the study carried out by Maharudrayya et al [17] some variation was noticed which was because the researcher has neglect the effect of inertia on his results [17].

All in all, the results obtained from experimenting with both designs of flow field plates was found to have good agreement with the results which obtained from theoretical studies published in [16-20].

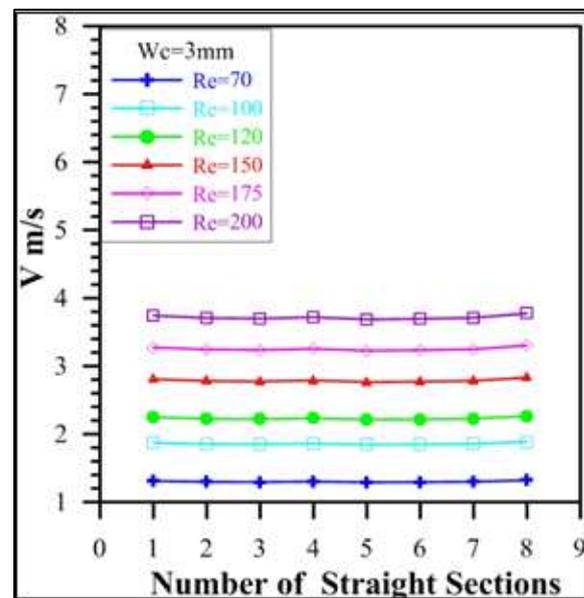


Figure 10: Single serpentine with different Re

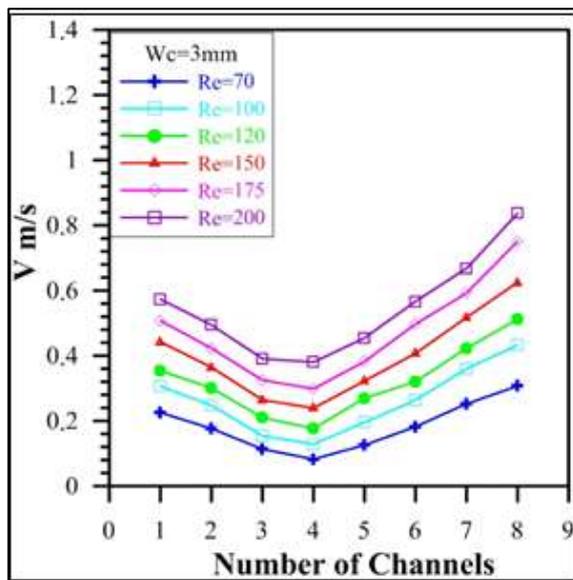


Figure 11: Parallel Z-type with different Re

#### 4. Conclusions

In this paper it was found the following results:

1- The new technique used in measuring mean velocity proved to be in good agreement with results that were obtained from theoretical studies.

2- In spite of the low values of Reynolds number that were used in the experimental work, the implemented technique gave good overall results. These results scored higher accuracies with increasing Reynolds number.

3- The cross correlation technique was successful in estimating mean velocity in each minichannel for both designs of flow field plates (single serpentine and parallel Z-type).

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