EXPERIMENTAL AND NUMERICAL ANALYSIS ON THE COOLING PERFORMANCE OF SYNTHETIC JET AT LOW REYNOLDS NUMBER

by

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
ANSYS	American Computer-aided engineering software
SCDM	SpaceClaim Direct Modeler

LIST OF SYMBOLS

V	Velocity
f	Driven frequency
t	Time
Q	Heat dissipation
h	Heat transfer coefficient
A_T	Total surface area of heater
T_s	Average temperature of the heat sink
T_∞	Ambient temperature
R_T	Total thermal resistance
T_h	Heater’s temperature
D	Distance between the orifices and the heat sink
Re	Reynolds number
D_h	Hydraulic diameter of the orifice
v	Kinematic viscosity of the fluid
Nu	Nusselt number
k	Thermal conductivity of the fluid

KAJIAN EKSPERIMEN DAN SIMULASI PRESTASI PENYEJUKAN JET SINTETIK PADA NOMBOR REYNOLDS YANG RENDAH

ABSTRAK

Jet sintetik adalah satu kaedah yang berpotensi dalam penyejukan mikroelektronik. Dengan ciri-ciri aliran bendalir aktif dan sifar aliran jisim bersih, jet sintetik merupakan satu peranti yang cekap dalam penyejukan mikroelektronik. Dalam kajian ini, prestasi penyejukan jet sintetik pneumatik disiasat dengan nombor Reynolds yang rendah. Kedua-dua eksperimen dan simulasi berangka dijalankan. Siasatan dijalankan dengan dua susunan yang berbeza. Udara yang dijana daripada rongga jet sintetik dihantar secara mendatar. Seterusnya, aliran udara dihantar secara menegak. Parameter-parameter kajian dilakukan berdasarkan lapan nombor Reynolds jet sintetik yang berbeza, kuasa dibekalkan kepada sink haba, dan jarak antara orifis dan sinki haba. Kajian ini menunjukkan bahawa peningkatan frekuensi jet sintetik meningkatkan halaju udara dan membawa kepada prestasi penyejukan yang lebih baik. Kajian ini juga menunjukkan bahawa pemalar pemindahan haba jet sintetik adalah dua kali lebih tinggi daripada perolakan semulajadi. Keputusan juga menunjukkan bahawa apabila kuasa yang dibekalkan meningkat, lebih tinggi nombor Nusselt dan secara tidak langsung membekalkan prestasi yang lebih baik dalam penyejukan jet sintetik. Walau bagaimanapun, sekiranya jarak antara orifis dan sinki haba ditingkatkan, prestasi penyejukan akan merosot. Jarak 0 cm menghasilkan 20% permindahan haba lebih baik daripada jarak 1 cm. Kajian ini juga menunjukkan susunan udara secara mendatar mempunyai prestasi penyejukan 8% lebih tinggi berbanding dengan susunan aliran udara menegak.

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ABSTRACT

Synthetic jet is a potential alternative for microelectronic cooling. With the active fluid flow characteristic and zero net mass flow, the synthetic jet has been considered as the high-efficiency device in cooling microelectronic devices. In this study, a pneumatic synthetic jet with low Reynolds number is investigated for the cooling performance of an aluminium heat sink. Both experimental study and numerical simulations are conducted. The investigations are carried out with two different arrangements. The air is generated from the synthetic jet in the cavity and delivers horizontally to the heated heat sink through the orifices. Another arrangement is vertical air flow delivered upward from the synthetic jet to the heated heat sink through the orifices. The characteristics study is performed at eight different Reynolds number of the synthetic jet, power supplied to the heat sink, and the distance between the orifices and the heat sink. The study shows that as the driven frequency of the synthetic jet increases, the airflow velocity also increases, and it leads to an improved cooling performance. The findings show that the heat transfer coefficient of the synthetic jet is two times higher than that of the natural convection. The results also show that as the power supplied increases, Nusselt number increased which lead to the better cooling performance of the synthetic jet. However, as the distance of the orifices to the heated heat sink increases, the cooling performance is eventually decreased. The distance of 0 cm results in 20% higher heat transfer coefficient as compared to the distance of 1 cm. The study also reveals that the horizontal air flow arrangement provides 8% higher cooling performance as it is compared to the vertical air flow arrangement.

CHAPTER ONE

INTRODUCTION

1.0 Overview

This chapter introduces the invention and general design of synthetic jet. The first section provides the research background of the synthetic jet. The second section highlights problem statement in the present study. The third section shows the present research aims and objectives. The fourth section presents the scope of study. The final section is an outline of the whole thesis.

1.1 Research background

Microelectronic devices are widely being used in the new modern era of the human society. With the high demand of the microelectronic devices, the usage of the devices increases with time. Thus, the reliability and optimum performance level of the microelectronic devices are the two important aspects of the design of the devices. Operating temperature such as ambient temperature, humidity, size of the devices and others are undeniable affected the reliability and performance of the microelectronic devices. But, the most common and usual factor that always decreases the reliability of the devices is the thermal overstressing. According to law of the conversion of energy, the energy cannot be created and destroyed. The energy can only be transferred from one form to another form with the constant total net energy. Microelectronic devices utilize the electrical energy and eventually releases the thermal energy. As the thermal energy increases, the temperature of the microelectronic device also increases. Microelectronic devices operate efficiently under the acceptable range of the operating temperature. Based on the research (Lall et al., 1997), the reliability of the devices decreases as microelectronic temperature exceed 100°C. The increasing temperature will increase the thermal stress on the devices which eventually decreases the lifespan, performance and the efficiency of the microelectronic devices.

Thermal control and appropriate cooling method of the microelectronic devices plays an important role in maintaining its reliability and performance. According to the Newton’s law of cooling, the thermal energy transfers from hot surface to the cold surface. Heat is first generated from the integrated components inside the devices and released to the devices’ surface. Lastly, heat is released from the heated surface of the devices to the ambient. In this work, heat transfers from the heated surface to the ambient is investigated with the suggested thermal management technique. Nowadays, the commercial cooling method is required to mitigate the high heat flux. There are three types of methods to dissipate the heat to the ambient which are the active cooling method, the passive cooling method and the combination of the active and passive methods. The active cooling method enhances the heat transfer with the help of external energy consumption. The cooling devices increase the rate of the fluid flow and ultimately remove the heat from the heated surface. Active cooling method is well believed as the considerable approach in heat transfer enhancement. Fan, blower, synthetic jet and others are the example of the active cooling technique. Passive cooling method increases the heat transfer rate with no additional energy consumption. Heat sink is an example of passive cooling method. This method increases the level of the heat dissipation rate and natural convection. Hybrid cooling technique is known as the combination of active and passive cooling method which is widely use in the computer power unit (CPU).

As the demand of the microminiaturization of integrated microelectronic devices increases, more effective and better cooling management is needed to remove the high heat dissipation level of devices. Synthetic jet is an active cooling approach which controls the operating temperature to an acceptable level. Synthetic jet has been widely developed and explored in the field of the microelectronic cooling system with its promising cooling technique in thermal management. This jet is called synthetic jet because air vortex ring is synthesized by the diaphragm (Smith & Glezer, 1998). Synthetic jet improves the fluid mixing and provides a better heat transfer in cooling the microelectronic devices. Synthetic jet consists of few parts such as the air cavity, diaphragm and orifice as shown in Figure 1.1. In general, a diaphragm is attached with the air cavity and the orifice is located opposite the diaphragm. The location of the diaphragm and orifice could be located at anywhere in the air cavity as it fits the requirement of the synthetic jet design. The synthetic jet is usually driven by electric system, pneumatic system, magnetic system, mechanical system, and others.

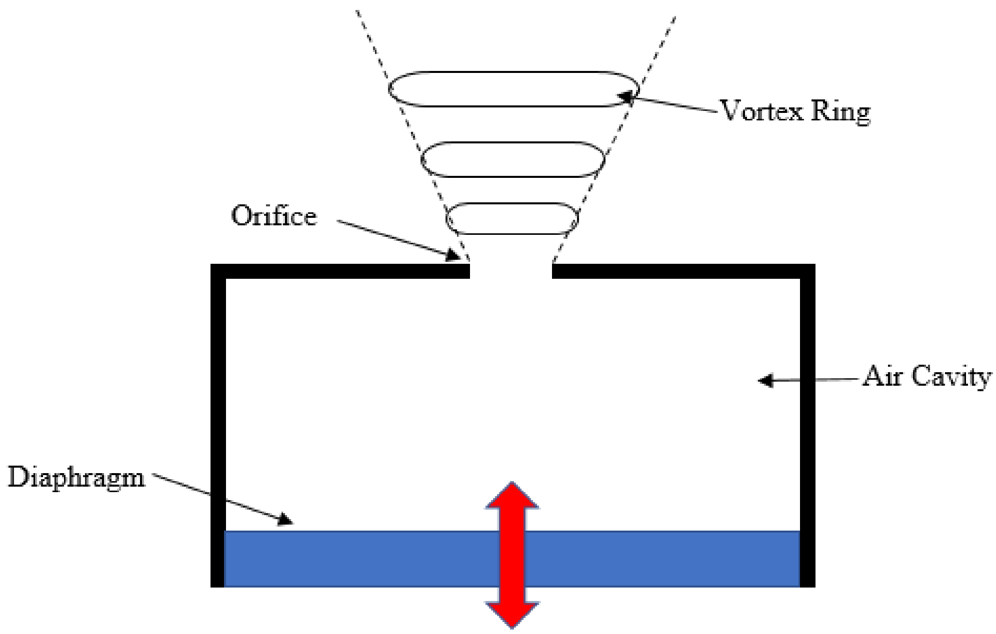

Figure 1.1 Synthetic jet

As shown in Figure 1.1, the diaphragm is forced to move upwards. This movement causes the fluid to be expelled out of the air cavity through the orifices. A vortex ring is generated at the end of the orifices and expelled out to the targeted surface. The diaphragm is then forced to move downwards. Once the diaphragm reaches a maximum displacement, fluid is then ingested from the surrounding area into the air cavity. This process is continued until the operation is stopped. The periodic movement of the diaphragm recycles the ambient air and provides a net mass of fluid that entrains in and expels out from the air cavity, with a value which is equal to zero. This attractive characteristic increases the application of synthetic jet in the microelectronic thermal management system. Besides, synthetic jet does not require any external air/fluid source to drive fluid flow to the targeted area. In this case, synthetic jets are therefore regarded as an extremely promising alternative to the steady cooling jet with high heat transfer capability.

1.2 Problem statement

Synthetic jet has been well believed to be a promising cooling scheme in the thermal management system. This has drawn the attention of the researchers, in a quest to investigate the cooling performance of the synthetic jet. Synthetic jet mostly is powered by speaker which produced the high Reynolds number of fluid flow and located in the impinging direction. Speaker produced high Reynolds number which has shown the promising synthetic jet performance at the impinging direction. But as the Reynolds number of the synthetic jet is increases, the power consumption by the jet is increases. The power consumption can be reduced as the Reynold number decreases. Reynolds number of fluid flow undoubtedly influence the cooling performance of the synthetic jet. Thus, low Reynolds number and horizontal direction has drawn the attention in the investigation.

1.3 Research objectives

The research aims to investigate the cooling performance of the synthetic jet. The main objective is to develop a pneumatic synthetic jet model, then investigate the cooling performance of the synthetic jet. The study objectives are:

1. To investigate the effect of different low Reynolds number from 0 to 163.2 of the synthetic jet and power supplied to the heat sink to the cooling capability of the synthetic jet.
2. To study the cooling performance of the synthetic jet at different distance between the orifice and the heat sink.
3. To identify the cooling performance of the synthetic jet at two different arrangement of the experiment (horizontal and vertical arrangement).
4. To validate the cooling performance of the synthetic jet simulation study to the experimental study.

1.4 Research scope

Synthetic jet has emerged as a cooling scheme in controlling the operating temperature of microelectronic devices to an acceptable level. In this research, a pneumatic synthetic jet is developed and modelled the cooling performance of the synthetic jet is studied at low Reynolds number (ranged from 0 to 163.2). There are some limitations that have been set in this research. The heat loss is negligible. The vibration of the synthetic jet system is neglected. The study also assumed ambient velocity in the test section is 0 m/s and air humidity is constant during the experiment.

CHAPTER TWO

LITERATURE REVIEW

2.0 Overview

This chapter reviews the literature on design and the cooling performance of the synthetic jet. It begins with a brief introduction of the design of the synthetic jet. Several factors that influence the cooling performance are explained next in the section. This includes the fluid flow characteristic of synthetic jet, orifice shape, stroke length of the synthetic jet and distance between the orifice and the targeted surface. Finally, a short summary about the characteristic of the synthetic jet is discussed.

2.1 Flow characteristic of synthetic jet

The high demands for high and better effective cooling of the microelectronic devices and the integrated devices leads to the innovation of synthetic jet. Synthetic jet is capable to manipulate the operating temperature to an optimum level and show promising features in thermal management for microelectronic cooling. Research on the synthetic jet as microelectronic cooling devices recently has been a popular topic. Synthetic jet consists of a diaphragm which is the main actuator of the system. The fluid flow is produced as the diaphragm move upward and downward periodically. Thus, the fluid flow plays an important role in developing the synthetic jet.

Mahalingam & Glezer (2004) had reviewed on the design and thermal characteristic of the synthetic jet. In their findings, the temperature of the high-powered heat sink reduced by 35℃ (from 71.5 ℃ to 36℃) as shown in Figure 2.1. This phenomenon eventually showed that synthetic jet is capable to act as the cooling device. Besides, from the study synthetic jet also transferred more heat rate (around

20%-40%) from the heated heat sink to the surrounding as it is compared to conventional fan. An experiment study on the heat transfer measurements of the synthetic jet by using the interferometry was carried out by Bhapkar et al. (2014). Their study focused on the effect of excitation frequency synthetic jet on the heat transfer rate by using interferometry. The findings showed the good agreement on the result between the interferometry measurement and the result measured from the thermocouple. The results also showed that as the exciting frequency of the synthetic jet increased, the average heat transfer coefficient also increased.

Qayoum et al (2010) had executed an experimental study on the laminar boundary layer heat transfer enhancement of the synthetic jet on the flat surface. The result revealed that the average heat transfer coefficient of the synthetic jet increased during the excitation of the voltage. Besides, the heat transfer coefficient also increased with the amplitude modulation at low frequencies. Liu et.al. (2015) had proposed an investigation of the piezoelectric actuator driven synthetic jet. The investigation was focused on the flow and heat transfer characteristics of the fluid which was produced from the synthetic jet. The results showed that heat transfer coefficient was highly depended on the driven frequency. The higher the driven frequency, the higher the heat transfer coefficient. Besides, it also showed that the synthetic jet is highly recommended cooling scheme which it was capable to provide 2-8 times heat transfer rate as it compared to natural convection.

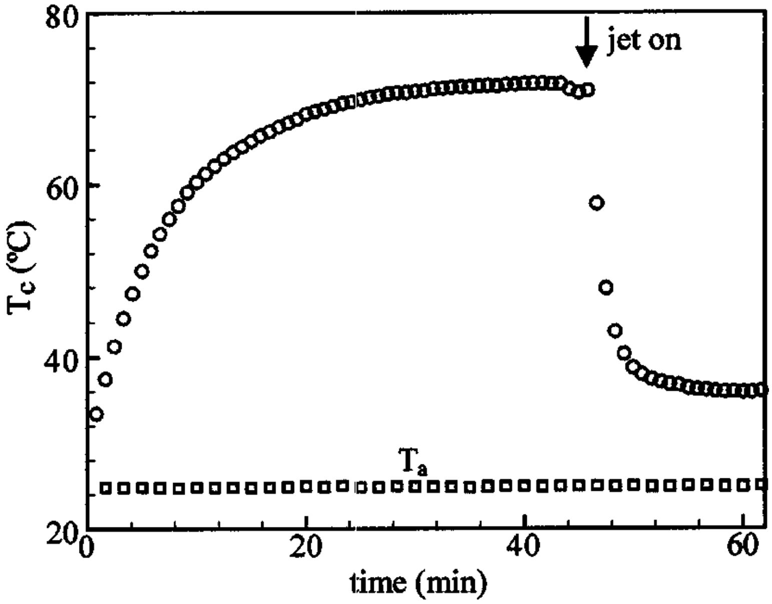

Figure 2.1 Rapid cooling capability of synthetic jet ejector heat

(Mahalingam & Glezer, 2004)

The vortex dynamic and heat transfer of the synthetic jet is investigated by Silva-Llanca & Ortega (2017). It shows that the heat transfer is influenced by the coalescence of the vortex that is produced by the synthetic jet. The collision between the heated wall and the secondary vortices leads to the reducing in the heat transfer of the jet. It also proves that the completion of vortex cycle is directly proportional to the Reynolds number and inversely proportional to the frequency of the synthetic jet. Convection instability is investigated by the previous researchers (Leigh et al. 2016). It shows that the unsteadiness of the flow was due to the boundary layer disturbance at the end wall plume. There are two modes of the excitation on convection flow which are the high frequency mode (7500 Hz) and the low frequency mode (4000 Hz). The study shows that higher frequency mode is achieved when small amplitudes is existed while the lower frequency mode is achieved when large amplitudes.

C.S. Greco et al. (2016) also investigates on the flow field of the single and twin circular synthetic jet. Twin circular synthetic jet provides higher turbulence level and axial velocity of the flow with a lower axial velocity phase than the single circular synthetic jet. A comparison between steady jet and synthetic jets with low aspect ratio rectangular orifice has been proposed by Van Buren & Amitay (2016) as shown in Figure 2.2. The findings show that synthetic jet provides a three times higher momentum than steady jet. Thus, synthetic jet shows a better capability of cooling performance in term of Reynolds number and Nusselt number.

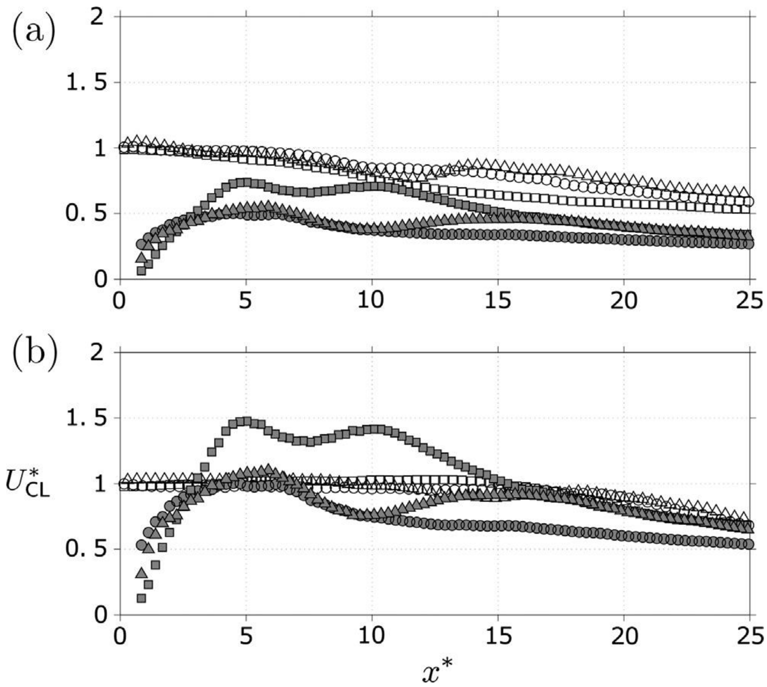

Figure 2.2 Downstream evolution of the centerline velocity for the steady (white symbol and synthetic (gray symbols) jets with aspect ratios AR = 6 (circle), 12 (square), and 18 (triangle). (a) velocity scales derieved from the entire actuation cycle and (b) velocity scales derieved from the blowing portion of the cycle by (Van Buren & Amitay, 2016)

Xia & Zhong (2014) studied an investigation on the enhancement of the laminar flow mixing of the synthetic jet. The findings showed that the driven frequency and the stroke length of the synthetic jet affected the performance of the synthetic jet. The result also showed that at high driven frequency or large stroke length, the well laminar flow mixing was achieved. An experimental study on the nearby flow field of the single and twin circular shaped synthetic jet had been proposed by Carlo Salvatore et al. (2013). Twin circular shaped synthetic jet generated a double vertex ring structure and it also produced high jet centerline velocity as it is compared to the single synthetic jet. McGuinn et al. (2013) also had investigated on the flow characteristics of the synthetic jet. The focus was the effect of the stroke length on the fluid flow of the synthetic jet. The findings showed a strong agreement that better heat transfer enhancement can be achieved by varying the stroke length of the synthetic jet as shown in Figure 2.3. As the stroke length of the synthetic jet increased, the amount of the fluid drawn in and out of the orifice increased which leads to the increasing in the heat transfer rate.

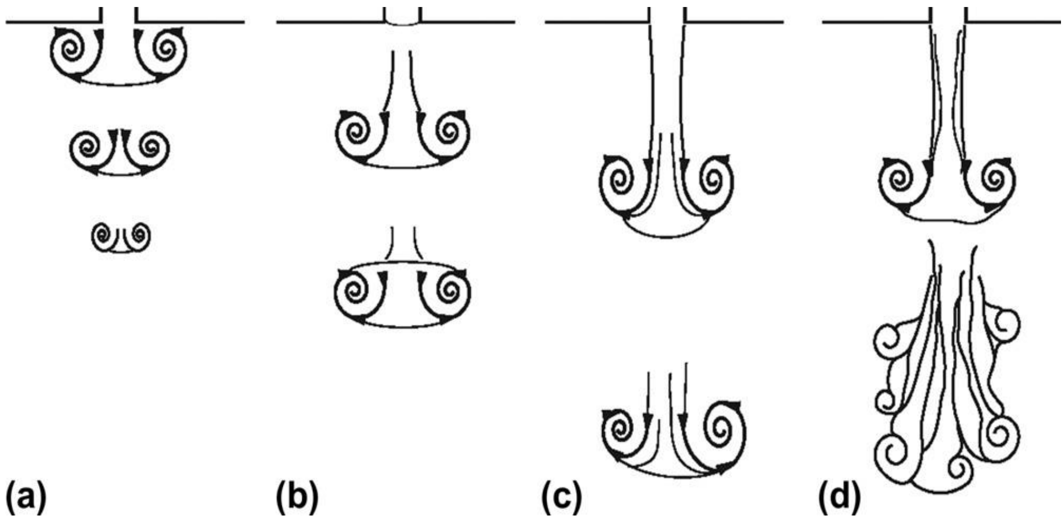

Figure 2.3 Flow morphology of vortex formation and evolution at various stroke

$\frac{(a)L_0}{D} < 4,\ (b)4 \le \frac{L_0}{D} < 8,\ (c)8 \le \frac{L_0}{D} < 16, \frac{(a)L_0}{D} \ge 16$ (McGuinn et al. (2013))

Feero et al. (2015) proposed an investigation on the cavity shape of the synthetic jet. In the investigation, three types of cavity shapes had been tested which are the cylindrical shape, conical shape and contraction shape. The findings showed a strong agreement that shapes of the cavity also affected the performance of the synthetic jet. The cylindrical shape cavity showed a better synthetic jet's performance as it is compared to the other two cavities at the largest momentum flux. Besides, an investigation of the effect of the cavity and orifice on the flow characteristic of the synthetic jet was performed by Jain et al. (2011). The result showed that the orifices played an important factor in the flow characteristic of the synthetic jet as shown in Figures 2.4 and 2.5. As the parameter of the orifices changed, the maximum fluid velocity can be achieved.

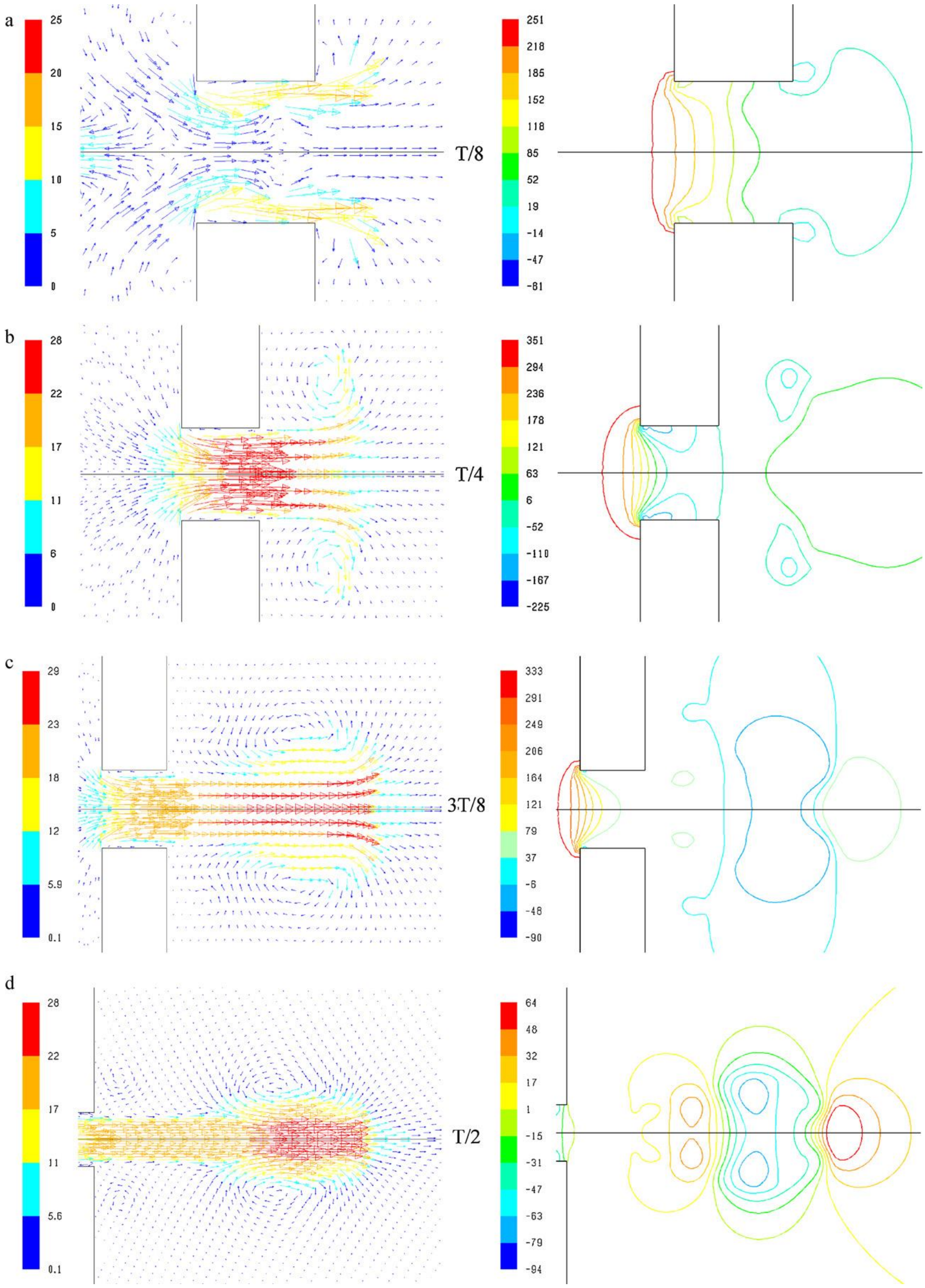

Figure 2.4 Velocity vectors (Right) and pressure contours (Left) for different times in a cycle of operation. Colour map for velocity vector showing magnitude in m/s. Pressure contour are for gage pressure and unit used is Pa (Jain et al. (2011))