PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering - Port Said University
Volume 18 No. 2 September2014 pp:42 : 50

Simulation Study of Screw Micro Pumps Design and Performance

Ezat, A.A. [1], El-Sawaf, I.A. [2], Mohamed, A.M.I. [3] and Hoettiba, R.[4]

ABSTRACT
Increasing efforts are being directed towards applying the technologies of micro-fluidic, to the development of micro-devices for a wide range of applications such as medical, biological, engineering and related technologies. The present studies are interested with the design of micro-screw pump for viscous fluid and its operating behaviour, the steady performance of the micro-pump will be investigated numerically. The present numerical investigation is a comparative study of a steady flow behavior in a micro-channel with rotating screw with different operation and design parameters. The numerical investigation is performed using computational fluid dynamic techniques. The FLUENT program as CFD simulation program in the ANSYS 14.0 package used to simulate the pump model. The results of the simulation problem give an agreement with literature experimental results which validate the simulation model that encourage future simulation of the studied system. Theoretical analysis by is carried out to study the influence of the helix angle, diameter of the screw, screw length and the thread height (flight depth) to evaluate the optimal dimensions for the pump to obtain the maximum flow rate and pump performance The effect of screw angular velocity and pump load were studied.

Key words: Micro-pump; Screw thread; Screw diameter; Helix angle

NOMENCLATURE

A	Effective area, m^2
c	Gab between screw and the casing, m
c_h	length of one turn of the helix curvature, m
D	Channel diameter, m
d	Screw diameter, m
e	Overall efficiency
K_n	Knudsen number
L	Channel length, m
l	Screw length, m
$\dot{m}$	Mass flow rate, kg/s
n	Number of revolution, 1/s
P	Pressure load, Pa
P_e	Power exit, W
Pi	Pitch, m
P_i	Power inlet, W
Q	Volume flow rate, m^3/s
R	Channel radius, m
Re	Reynolds number, Re
r	Radius of the screw, m
t	Distance between the root of two teeth, m
th	Teeth height, m
U	Bulk velocity, m/s
u_s	Screw velocity, m/s
V	Tangential velocity, m/s
X	Teeth width, m

Greek Symbols

θ	Helix angle, degree
μ	Dynamic viscosity, Pa.s
ρ	Density of liquid, kg/m^3
τ	Shear stress, Pa
υ	Kinematic viscosity, m^2/s
ω	Angular velocity, rad/s

Subscripts

sh	Shaft
v	Volumetric
th	Theoretical
real	Actual
in	Inlet
out	Outlet

1. INTRODUCTION
Archimedes screw, one of the oldest machines still in use, a device for lifting water for irrigation and drainage purposes. Its invention has traditionally been credited to Archimedes. For example, Diodorus Siculus (Greek historian) writes men easily irrigate the whole of an island in the delta of the Nile by means of a certain instrument conceived by Archimedes of Syracuse, [1,2].

Micro devices have a wide range of application such as medical, biological, engineering and many others.

Large viscous forces in relation to inertia are one of the main difficulties to run micro-machines that are simply reduced in size may not work. At such small scales, conventional principles of rotating turbo-machinery based on centrifugal and inertial forces are not very useful. Since viscous forces tend to be important at small scales, a pump based on viscous action seems to be logical.

The rather high Reynolds numbers involved are not typical of micro-scale devices, however, and the device is too complicated for micro-fabrication.

Micro-pumps operate as a result of completely different principles than those applied in traditional pumps like the axial or centrifugal pumps. Micro dimensions limit the effect of centrifugal forces and inertia forces in general, and the large surface-to-volume ratio amplifies the effect of viscous forces, rendering it the dominant force at the micro-scale [3]. Positive displacement pumping is the most prevalent method used in micro-pumps.

Micro-pumps are used in ink jet printers, as a pressure supplies for micro-machines, and microelectronic cooling.

Many workers investigated the different behavior of the micro pumps. Zheng, P. [4] the performance of mini and micro devices driven magnetically through simulations and experiments. Micro-Electro-Mechanical Systems (MEMS) invoking magnetic coupling were designed and tested. Magnetic devices can generate larger forces for larger distance than their electrostatic counterparts; the energy density between the magnetic plates is usually larger than that between the electric plates.

El-Sadi, H., et al [5] investigated numerically the performance of micro screw pump using complex liquid. The micro screw pump operation depends on the surface sweep forces. It consists of a screw placed inside a micro channel. When the screw rotates, a net force is transferred to the fluid due to differential pressure on the depth of the thread and pressure gradient along the screw axis, thus causing the fluid to displace. The simulations of complex liquids indicate that the highest bulk velocity is achieved with high thread depth at low Reynolds number.

El-Sadi, H. and Esmail [6] studied the transient performance of the micro-pump numerically. The numerical investigation is a comparative study of transient flow behaviour in a micro-channel with rotating screw with different cross-sectional geometries, and concluded that the thread depth was the most crucial parameter affecting the pump transient performance.

The thread provided the driving force to the fluid inside the channel by introducing pressure difference in the thread gap in addition to the pressure gradient along the screw axis. The lift coefficient is smaller than the drag coefficient due to the differential pressure on the thread depth. The range of the efficiency of the micro-pump was between 3 and 75% depending on the dimensions of the micro-pump and the properties of the fluid.

Bataineh, K. M. and Al-Nimr. M. [7] studied the performance of the pumps and the effect of velocity slip on its performance. Mass flow rate and pump efficiency were calculated for various pump operation conditions when an external pressure load was applied at the pump exit plane. And concluded that the pump efficiency varies with external imposed pressure and slip. However, for fixed slip factor and external pressure, pump efficiency stays almost constant with varying Reynolds number in the present study range. For the given Reynolds number, maximum efficiency occurs around half of the maximum pressure that the pump could deliver. Maximum pump efficiency increases with increasing slip factor. Slip velocity degraded pump performance

Abdelgawad, M., et al [8] investigated numerically the transient performance of the viscous micro-pump. The viscous micro-pump's operation depends mainly on viscous forces and could operate in any situation where viscous forces were dominant. All the micro-pump calculations were reported in nondimensional quantities, which allows for the prediction of the micro-pump performance, regardless of the dimensions or the fluid that is used. Higher eccentricities were able to generate high backpressures, yet the pumping efficiency was lower than that for cases of relatively lower eccentricities. Depending on the value of the backpressure and cylinder eccentricity, the pump start up in some cases was characterized by a backflow followed by a positive flow, or vice versa.

El-Sadi, H. and Esmail, N. [9] investigated the effect of using various screw geometries on the pump performance. Theoretical analysis by finite volume simulations is carried out to study the influence of the screw pitch and the thread (flight depth) to evaluate the optimal dimensions for the pump and to obtain the maximum flow rate. When the screw rotates, a net force is transferred to the fluid due to the differential pressure on the depth of the thread and pressure gradient along the screw axis, thus causing the fluid to displace. The simulations revealed a gradual increase of the pump performance as the screw diameter decreases. However, effective pumping was accomplished with increasing screw thread. The thread provides the driving force to the fluid inside the channel by introducing pressure difference in the thread gap in addition to the pressure gradient along the screw axis.

Nakao, M., et al [10] investigated the development of a micro screw pump for discharging effusion from middle ear for treatment of otitis media. This tool extrudes effusion using a newly designed screw, which rotates at 90,000 rpm in a pipe penetrated through tympanic membrane. This tool satisfies the discharge performance especially for high viscosity effusion while it has smaller diameter such as about 0.5 mm. Also performed clinical application to prove its feasibility usage.

Choi, J.P., and et al. [11] proposed a synthetic jet-type micro-pump for supplying air. Synthetic jet actuators usually include a small single pumping cavity, inlet/outlet channels, and a Lead Zirconate Titanate membrane that exerts the pumping pressure. To determine the optimum design parameters of the air pump, a numerical analysis was carried out by varying its geometry. The optimized air pump was fabricated by replicating parts from silicon masters patterned by the deep process. The size of the fabricated micro-pump was 16 × 13 × 3 mm^3. In order to control the frequency of the PZT membrane and reduce the controller size and power consumption. At a pumping frequency of 80 Hz, a flow rate of 9.5 cc/min, pumping pressure of 438 Pa, and power consumption less than 0.15 mW were achieved.

2. THEORETICAL MODEL ANALYSES

The flow characteristic could be defined from the main assumption of the model as 3D, incompressible fluid. For this layer of flow the Navier Stock's equation can be demonstrated the phenomena of the flow inside the pump. The main assumptions and Navier Stock's equations of the problem which consist of: Continuity equation and momentum equation in the three dimensions as follow.

Continuity equation

$$\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z} = 0 \tag{1}$$

Momentum equations

In X direction

$$u\frac{du}{dx} + v\frac{du}{dy} + w\frac{du}{dz} = -\frac{1}{\rho}\frac{dp}{dx} + \mu\left(\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2}\right) \tag{2}$$

In Y direction

$$u\frac{dv}{dx} + v\frac{dv}{dy} + w\frac{dv}{dz} = -\frac{1}{\rho}\frac{dp}{dy} + \mu\left(\frac{d^2v}{dx^2} + \frac{d^2v}{dy^2} + \frac{d^2v}{dz^2}\right) \tag{3}$$

In Z direction

$$u\frac{dw}{dx} + v\frac{dw}{dy} + w\frac{dw}{dz} = -\frac{1}{\rho}\frac{dp}{dz} + \mu\left(\frac{d^2w}{dx^2} + \frac{d^2w}{dy^2} + \frac{d^2w}{dz^2}\right) \tag{4}$$

The geometry of an Archimedes Screw has been governed by certain external parameters (its outer radius, length and slope) and internal parameters (inner radius, number of teeth and its pitch). As the pump worked the glycerine will flow circumferentially throw the inlet as shown in Fig. 1.

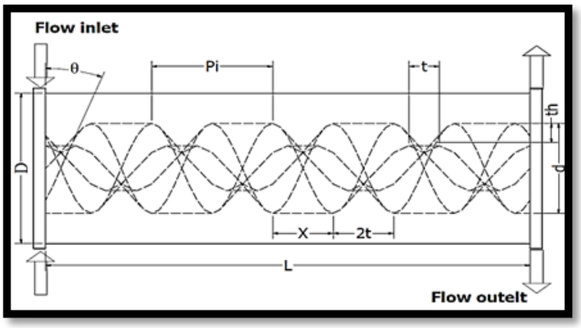


Fig. 1 Details drawing of the micro-pump.

The screw will be rotated with several angular velocities during this study with range [564-56471] rad/s. The variation of angular velocity induced variation of Reynolds number higher than for an equivalent volume of water.

The model was built in three dimensions. The whole model was built to be one component because of the model composed of many components that will be more complicated to be meshed by ANSYS 14.0 mesh program.

After applying the effect of mesh grid stability for different number of elements on two important phenomena mass flow rate and velocity magnitude found the suitable number of unstructured meshes as triangle is 1133685 elements

FLUENT 14.0 used as solver programme for simulation model. The pressure based solver type is used with steady, laminar viscous Glycerine flowing fluid. Inlet and outlet pressure are used as boundary conditions. The screw angular velocity also used as a boundary condition. The solution method is simple. Using the full multi grid initialization is considered the more convenient method to converge the solution small time as compared with other solution initialization techniques. The iteration number was 1000 iterations

3. VALIDATION

The results obtained from the computational fluid dynamics simulation model must be validated by comparing these results with literature experimental results [12] obtained at same operating conditions (th = 0.45 mm, L = 8 mm, Pi = 2 mm, X = 1 mm, θ = 29^o, d = 1.8 mm). This validation is investigated to prove the accuracy of the executed simulation program.

Figure 2 shows the velocity vector scaled in colour by velocity magnitude. It's clearly shown that the direction of the screw rotation takes counter clock wise. Theoretically, the liquid must obeys the screw rotation to rotate with the same angular velocity and the same direction but the liquid in the shear layer obeys the screw. The shear effect will be reduced in the radial direction (from the screw centre line to the wall) to reach a neglected value near the wall so the effect of leakage flow will be appeared as a back flow direction arrows.

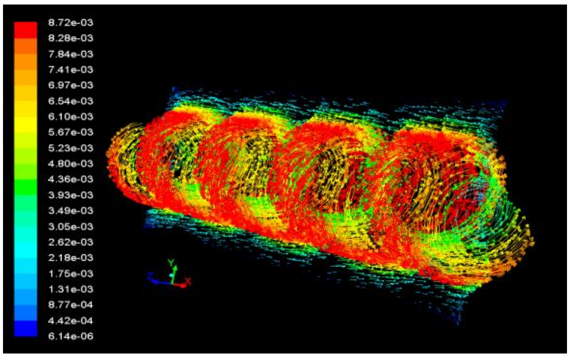


Fig. 2 Velocity vector at ω = 9.82 r.p.m., p = 4.91 Pa.

Figure 3 shows the magnitude velocity contour at ω = 9.82 rpm and p = 4.91 Pa in transversal plane. The red colour at the screw means high velocity for the fluid which in contact with the screw. The velocity decreases gradually until reaching a very low velocity at the layer near the casing wall.

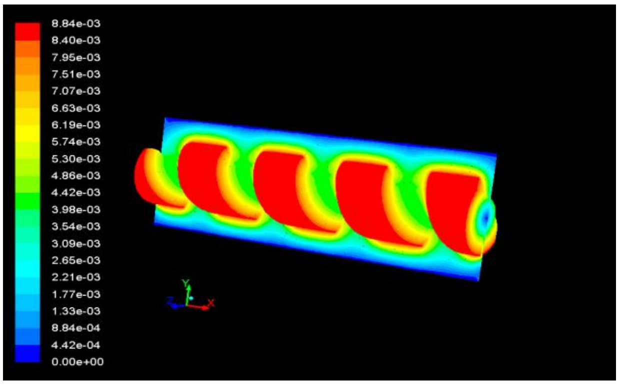


Fig. 3.Velocity contour at ω = 9.82 r.p.m., p = 4.91 Pa.

Figure 4 shows the comparison between the numerical simulation and the experiment. It can be noticed that the numerical results are 6–15% as close as to the experimental results. This deviation due numerical simulation error.

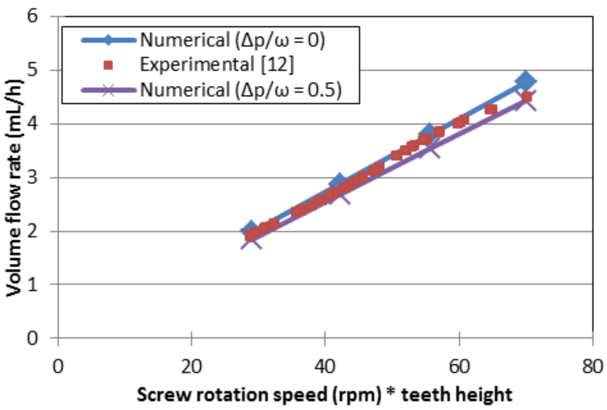


Fig. 4 Experimental and numerical results at different (Δp/ω).

4 RESULTS AND DISCUSSION

The effect of the design and operational parameter simulation results will be investigated, which obtained from the model of the present work. Also, this result will be analysed, a set of simulations are conducted with glycerin as a working fluid. The effect of different design parameters such as the teeth height, diameter, length and helix angle of the screw will be studied. In addition, the operational parameters variation will be investigated such as pressure, angular velocity, Reynolds number and flow rate.

4.1 Effect of the screw teeth height

The screw thread is a very important parameter in determining the pump performance, Fig. 5. The thread provides the driving force to the fluid inside the channel in addition to drag forces, by introducing pressure difference in the thread groove.

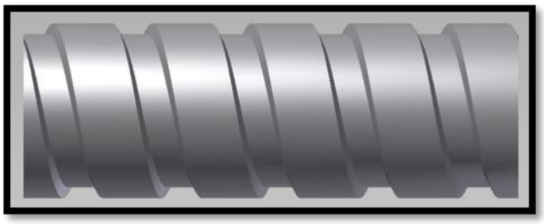


Fig. 5 Screw teeth = 0.18 mm and l = 5 mm

With increasing the screw teeth height value the effect of the Reynolds number of the pump performance has the same trend but at different values. It is clear that when the teeth height increases the steady-state average velocity increases inside the channel and hence the volume flow rate increases. This is due to the fact that increasing the screw teeth height increases the mass- flow rate inside the channel and therefore more force is required for the viscous forces of the fluid to overcome the inertia of the fluid. If the thread groove is very small, low net flow will start as shown Fig.6

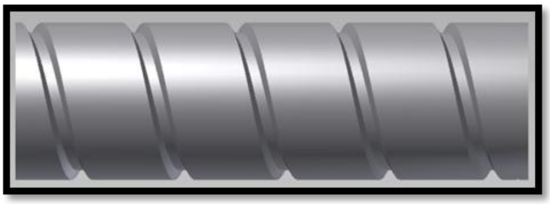


Fig. 6 The screw teeth = 0.09 mm and l = 5 mm.

The micro-pump performance as shown in Fig. 7 give the relation of the volume flow rate with pressure difference both divided by Reynolds number at certain screw length which was 5 mm but with varying screw teeth height th = 0.09 mm and th = 0.18 mm.

Figures 8 and 9 shows the velocity magnitude contours at different teeth height

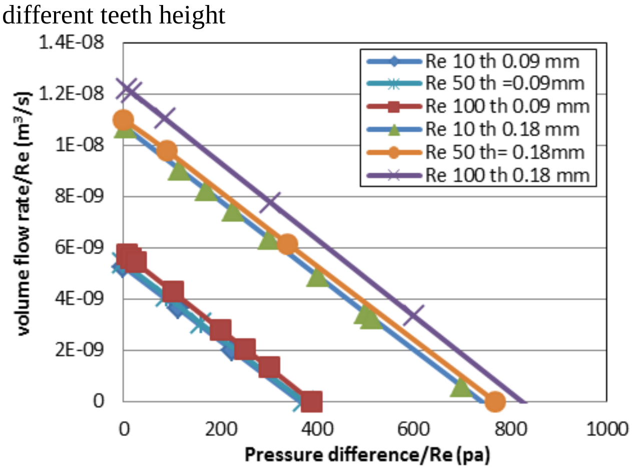


Fig. 7 Comparison of performances of micro screw pump at th = 0.18 mm, th = 0.09 mm and L= 5 mm.

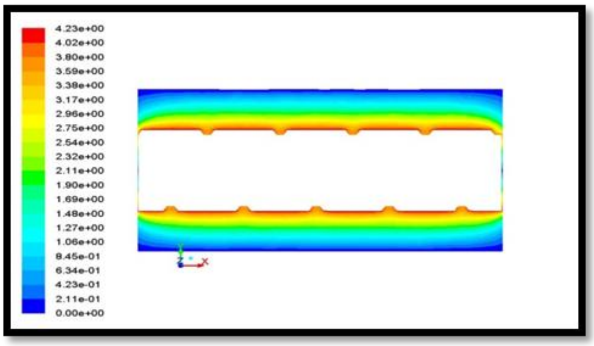


Fig. 8 Velocity contour at th = 0.09 mm, L = 5 mm and screw Reynolds number = 10.

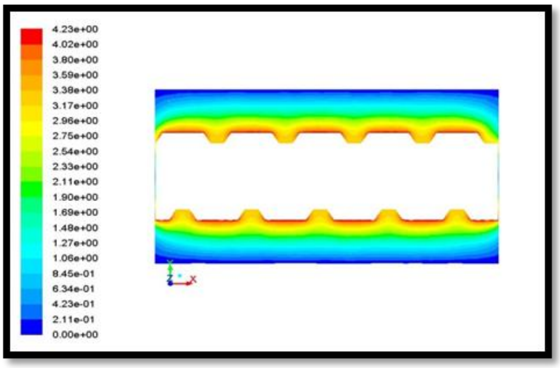


Fig. 9 Velocity contours at th = 0.18 mm, L = 5 mm and screw Reynolds number = 10.

4.2 Effect of screw length

The screw length is one of the most important parameters, that affects on the pump performance. In this section the performance will be investigated with increasing the screw length to be 8 mm. As shown from Fig. 10 at the screw teeth height equals 0.09 mm and two different screw lengths, the behaviour of the pump still has the same trend but at different slopes with different pressure difference and volume flow rate. At high value of screw length, the performance line showed an improvement than the line for the shorter screw. Figure 11 shows the velocity magnitude contour for two screw pump two with different lengths.

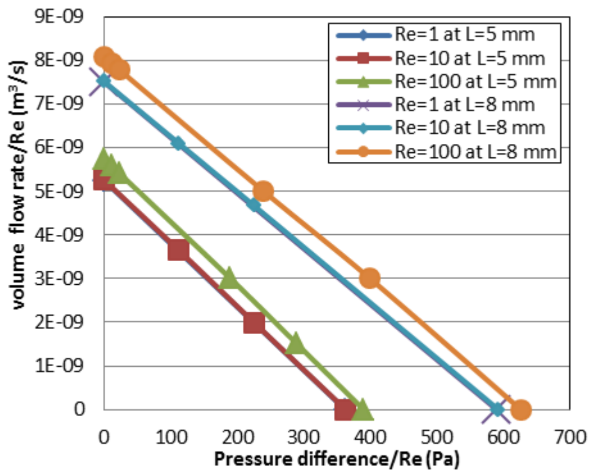
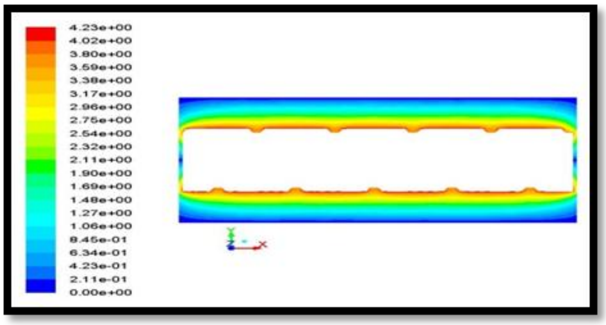
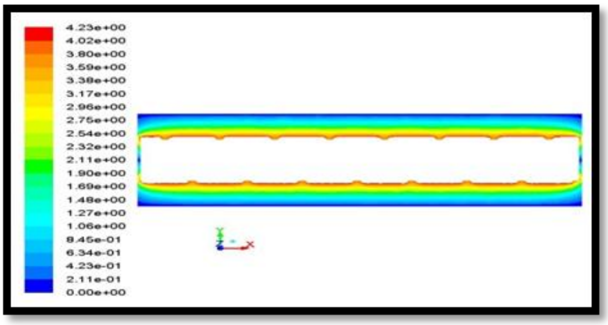


Fig. 10 Comparison between pump performances at

different lengths and th= 0.09 mm.



(a) Screw length = 5 mm .



(b) Screw length = 8 mm

Fig. 11 Comparison between velocity contours at different lengths and th = 0.09 mm.

Figure 12 shows a comparison between performance lines at (th = 0.09 mm), (L = 5 mm) and (th = 0.09 mm), (L = 8 mm) with (th = 0.18 mm), (L = 5 mm). The highest performance of the micro-pump is achieved when (th = 0.18) and (L = 5 mm). Whenever, the effect of increasing the teeth height on the pump performance is larger than the effect of increasing the screw length at same conditions.

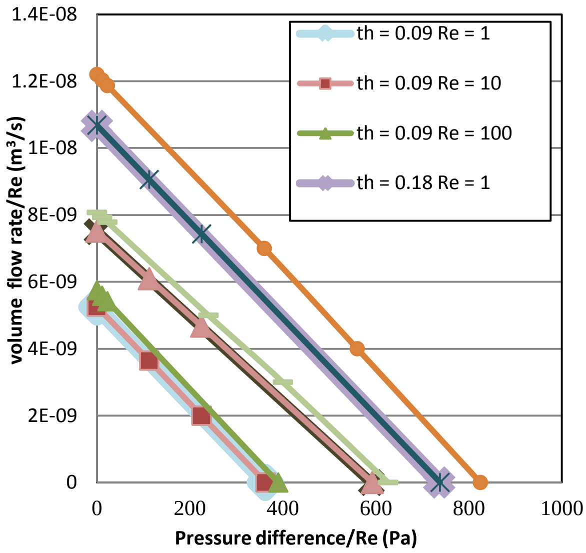
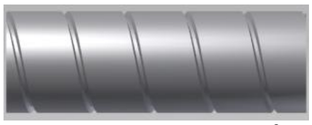


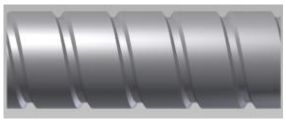
Fig. 12 Comparison of pump performances at different conditions.

4.3 Effect of the helix angles

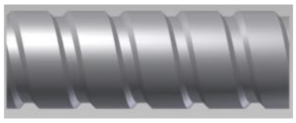
The present study shows the effect of screw helical angle on the average pump volume flow rate. Fig. 13 shows the screw of the pump with different helix angles 29°, 49°, 59° and 69°



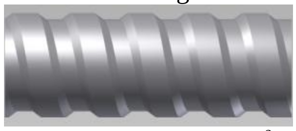
Screw helix angle = 29°.



Screw helix angle = 49°.



Screw helix angle = 59°.



Screw helix angle = 69°.

Fig. 13 Screw at different helix angles

Figure 14 shows the variation of the pump average volume flow rate for different screw helical angles at Re = 10, teeth height equals 0.09 mm, screw length equals 8 mm, pitch equal 1.6 mm, shaft diameter equals 1.32 mm and pressure difference equal 1126 Pa. It is clear that when the helical angle is increased, the average volume flow rate increases slightly till 49° then decreases sharply. This is due to the variation of the pressure gradient and the shear stress which is acting on liquid element along the screw axis

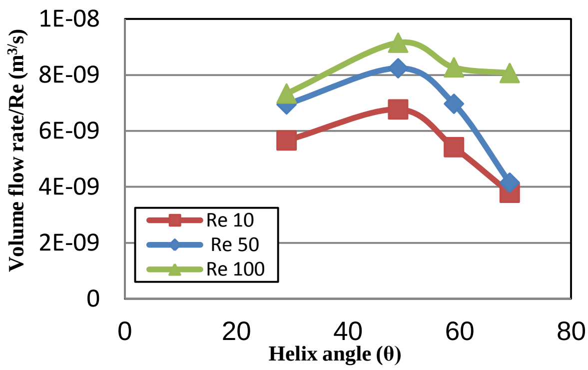


Fig. 14 Volume flow rate versus helix angles.

4.4 Effect of diameter

Figure 15 shows the volume flow rate curve as a function of the diameter. Where the pitch equals 1.6 mm, the teeth height equals 0.18 mm, the helix angle equals 29° and the screw length equals 8 mm. It is observed that the volume flow rate increases with increasing the screw diameter.

Increasing the screw diameter will reduce the distance between the channel wall and the screw and causes a decrease in the viscous resistance to the flow and a subsequent increase in the velocity. At the begin of increasing the flow rate the trend has sharp tendency, while after certain diameter (which is 2 mm) the increasing tendency was reduced, as showing in Fig. 16. This is due to the reduction of the area of flow passage at the high values of the screw diameter

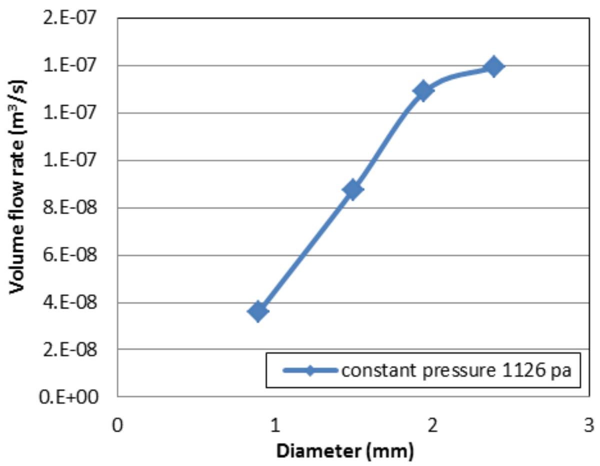


Fig. 15 Volume flow rate as a function of diameter.

5 VOLUMETRIC EFFICIENCY

The effect of the design and the operational parameters will be studied from the volumetric efficiency point of view.

Theoretical volume flow rate equation can be calculated from the next equation, [13].

$$Q_{th} = A * n * Pi \qquad (5)$$

Where:

$A = \frac{\pi}{4}\left(d^2 - d_{sh}{}^2\right)$ effective area

n number of revolution per second (1/s)

Then, the volumetric efficiency equation reads

$$e_v = \frac{Q_{real}}{Q_{th}} \qquad (6)$$

5.1 The teeth height effect

Figure 16 shows the effect of changing the teeth height (flight depth) on volumetric efficiency for different Re and pressure difference. This effect will be studied with different Reynolds number 10, 50 and 100 at screw length equals 5mm. From Fig. 16 at constant th and Re increasing in the pressure difference leads to linear reduction in the volumetric efficiency. This is achieved at all values of teeth height and Re, as the previous, the performance lines of high values of Re show high values of volumetric efficiency.

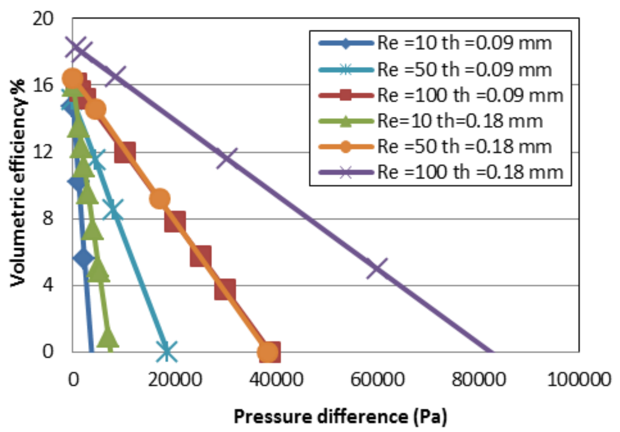


Fig. 16 Effect of the flight depth on the volumetric efficiency.

5.2 Screw length effect

The effect of increasing the screw pump length on the volumetric efficiency as shown in Fig. 17 has nearly the same effect of pump performance lines.

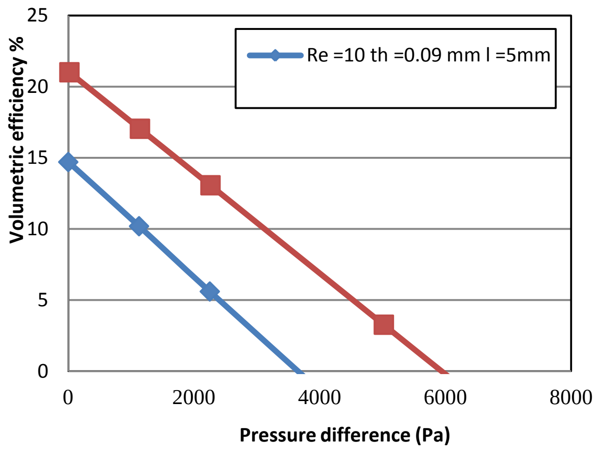


Fig.17 Screw length effect on the volumetric efficiency.

5.3 Effect of helix angle

As shown in Fig.18 the influence of increasing the helix angle on the volumetric efficiency has the same trend as its effect on the volume flow rate, slightly increase in the volumetric efficiency until certain angle 49^o then the volumetric efficiency starts to decrease with increasing the helix angle. Hence if there is need for high flow rate angle 49^o is the best choose for this screw pump

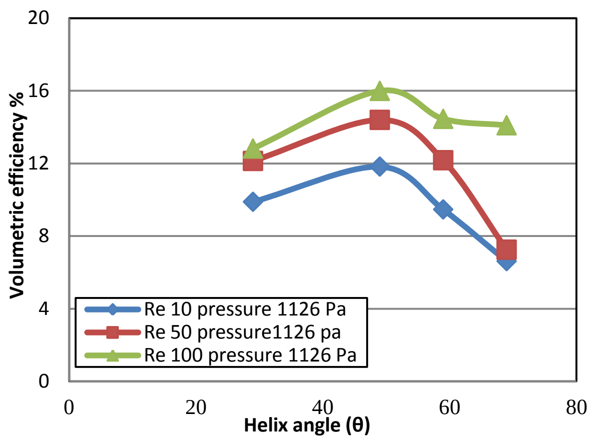


Fig. 18 Helix angel effect on the volumetric efficiency.

5.4 Effect of screw diameter

Figure 19 shows that increasing the screw diameter followed by increasing in volumetric efficiency

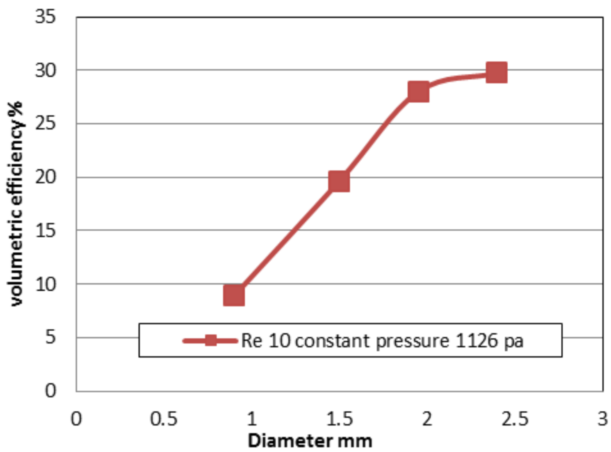


Fig. 19 Effect of change of diameter on the volumetric efficiency.

6 OVERALL EFFICIENCY

The pumping efficiency is a very important parameter to deliberate when the performance of any pumping device is studied. The micro-pump efficiency can be defined as:

$$e = \frac{\text{Flow energy rise}}{\text{Input mechanical energy}} \tag{7}$$

A measure of the micro-screw pumping efficiency is given by the valuable flow power produced to the input energy to the pump. The overall efficiency e can be obtained from this equation, [4]:

$$e = \frac{\Delta P^{*}(D^{2}-d^{2})u^{*}}{4\tau^{*}(d*l-th*c_{h})} \tag{8}$$

Where:

$$\Delta P^{*} = \frac{P_{out}-P_{in}}{\frac{\rho \upsilon^{2}}{d^{2}}} \tag{9}$$

$$\tau^{*} = \frac{\tau}{\mu u_{s}/l}\sin\theta \tag{10}$$

$$u^{*} = \frac{U}{\omega r} \tag{11}$$

Hence all superscripts * mean a dimensionless value

Then the overall efficiency equation is

$$e = \frac{\Delta p * Q * d * pi}{\pi^{2} * \tau * \upsilon * l(d*l - th*ch)\sin\theta} \tag{12}$$

6.1 Teeth height effect

After investigating the effect of increasing teeth height on the pump behaviour and the volumetric efficiency, the influence on the overall efficiency will be investigated.

As shown in Fig. 20 the high variation which is observed in the total efficiency between the teeth height 0.09 mm and 0.18 mm at screw Reynolds number equals 10 and at the same length 5 mm.

The increasing of the pressure causes increases in the overall efficiency until certain pressure value, then the increasing in the pressure causes reduction in overall efficiency.

This can be explained as in the begin when the pressure is at low value, the leakage is small and its effect on the pump flow is negligible. When the pressure is increased to a certain value (max point), the leakage will be increased and has a great effect on the reduction of the flow rate, which causes decreasing of the pump overall effect.

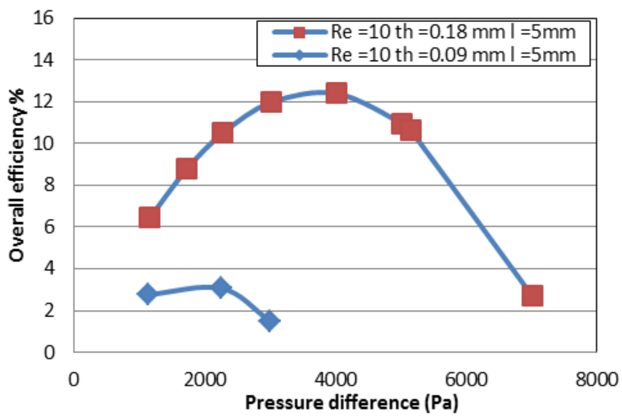


Fig. 20 Efficiency comparison between th = 0.09 mm and th = 0.18 mm.

Figure 21 shows the effect of the teeth height on the overall efficiency at screw Reynolds number equal 50, while Fig. 22 presents the same effect at Reynolds number equals 100

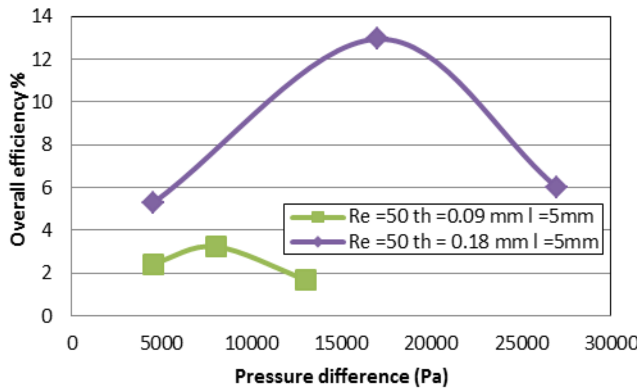


Fig. 21 Efficiency comparison between th = 0.09 mm and th = 0.18 mm.

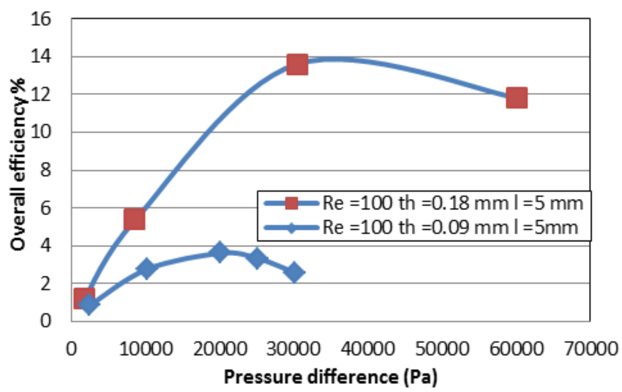


Fig. 22 Efficiency comparison between th = 0.09 mm and th = 0.18 mm.

From the previous investigation, Figs 21 and 22, it's noticeable that increasing the teeth height followed by increasing the overall efficiency. Also the increasing of the screw Reynolds number offset by slightly increasing in the efficiency but on the other side its offset by high increasing in the pump sustained load.

6.2 Screw length effect

The influence of changing the screw length on the overall efficiency is presented in Fig. 23 it is clear that increasing the length causes increasing in the overall efficiency and pump load at the same Reynolds number

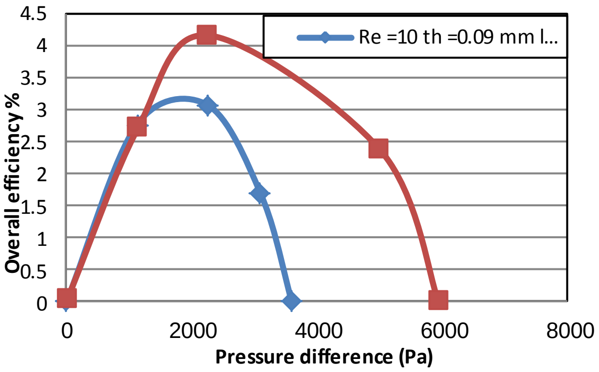


Fig. 23 Efficiency comparison at Screw Re = 10, l = 5 mm and l = 8 mm.

6.3 Effect of helix angle

The effect of helix angle on the overall efficiency is investigated as shown in Fig 24. It's found that by increasing the helix angle the overall efficiency increases until certain angle 59^{o} after that the efficiency decreases.

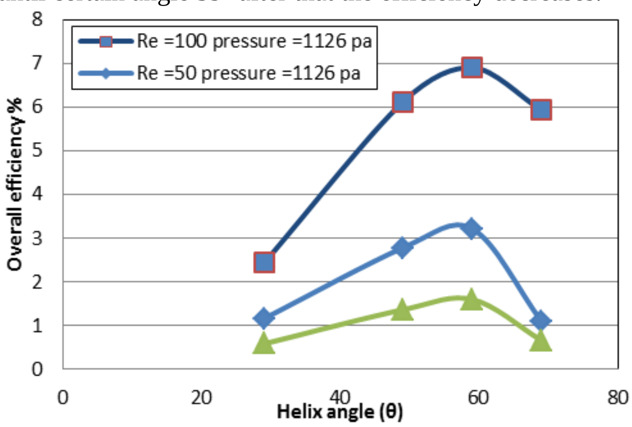


Fig. 24 Efficiency comparison at different helix angle and Re.

6.4 Effect of screw diameter

As shown in Fig. 25 the effect of increasing the screw diameter at constant screw Reynolds number is investigated. Increasing the screw diameter does not increase the overall efficiency at all as its effect on the pump behavior and volumetric efficiency. But offset by increasing in the total efficiency until certain value of the diameter equals 1.5 mm after that the total efficiency sharply decreases.

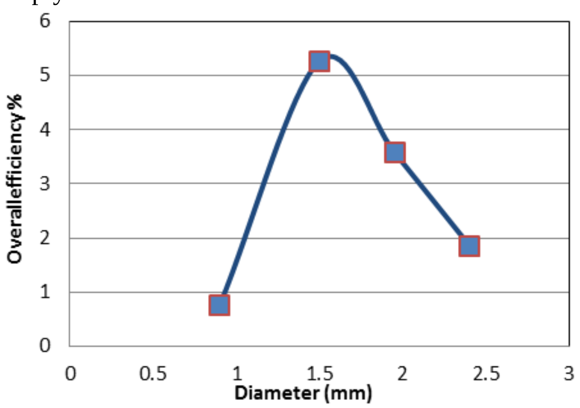


Fig. 25 Efficiency at Screw Re = 10 and constant pressure at different screw diameter.

However, the overall mass flow rate increased with increasing the diameter, but the energy addition per fluid particle will be small thus minimizing the efficiency

7 CONCLUSIONS

The present study investigates the design and the behaviour of positive displacement micro-screw pump. The effect of variation of design and operation parameters is studied. The next conclusions can be obtained from the study

1- The pump performance has a general trend which as the pressure difference increases the pump flow rate decreases at all working conditions.

2- As the Reynolds number increases the pump performance increases to give a higher pump flow rate values.

3- When the teeth height increases the steady-state average velocity increases inside the channel and hence the volume flow rate increases.

4- The influence of increasing of the screw length is clearly observed on the pump performance such that the behaviour of the pump will be increased.

5- The slope of the pump performance has been changed as the screw length changed.

6- The effect of increasing of the teeth height on the pump performance is larger than the effect of increasing the screw length at same conditions.

7- The increasing of the helix angle indicates an increasing in the pump behaviour until certain angle equal 45^{o}. As a threshold level by increasing the helix angle the pump behaviour sharply decrease.

8- Depending on the value of the angular velocity the effect of the screw diameter on the pump performance has different effect, as the diameter increase the outlet flow rate of the pump increase at high angular velocity but as the diameter increase the outlet flow rate of the pump initially increase then has constant value at low angular velocity.

REFERENCES

[1] Rorres, C., 2000, "Optimal Design of an Archimedes Screw", Journal of Hydraulic Engineering, Vol. 126, pp. 72-80.

[2] http://en.wikipedia.org/wiki/De_architectura

[3] Sen, M., Wajerski, D. and Gad-el-Hak, M., 1996 "A Novel Pump for MEMS Applications", Journal of Fluids Engineering, Vol. 118, pp. 624–627.

[4] Zheng, P., 2004, "Magnetic MEMS and its Applications", Ph.D. Thesis, the Florida State University College of Engineering

[5] El-Sadi, H. and Esmail, N., 2005, "Simulation of Complex Liquids in Micropump", Microelectronics Journal Vol. 36, pp. 657-666.

[6] El-Sadi, H. and Esmail, N., 2006, "Simulation of Three-Dimensional Transient Performance in Micro-Pump", Sensors and Actuators, Vol. 115, pp. 510-518.

[7] Bataineh, K. M. and Al-Nimr. M., 2009, “2D Navier–Stokes Simulations of Microscale Viscous Pump With Slip Flow”, Journal of Fluids Engineering, Vol. 131, 051105 (1-7).
[8] Abdelgawad, M., Hassan, I. and Esmail, N., 2004, “Transient Behavior of The Viscous Micropump”, Microscale Thermo Physical Engineering, Vol. 8, pp. 361-381.
[9] El-Sadi, H. and Esmail, N., 2005, “The Effects of Screw Geometry on the Pumping Efficiency of Micro-Screw Pump”, Canadian Journal of Chemical Engineering, vol. 83,
[10] Nakao, M., Okusa, T., Rahim, A., Matsumoto, K. and Hatamura, Y., 2001, “Micro Screw Pump to Discharge Effusion from Human Middle Ear”, Department of Engineering Synthesis, The University of Tokyo.
[11] Choi, J. P., Kim K. S., Seo, Y. H. and Kim, B. H., 2011, “Design and Fabrication of Synthetic Air-Jet Micropump”, Springer, Vol. 12, pp. 355-360.
[12] El-Sadi, H. and Esmail, N., 2006, “Simulation of Three-Dimensional Transient Performance in Micro-Pump”, Sensors and Actuators, Vol. 115, pp. 510-518.
[13] Xu, J., 2008, “Modeling of Wet Gas Compression in Twin-Screw Multiphase Pump”, Ph.D Thesis, Submitted to the Office of Graduate Studies of Texas A&M University.
[14] Ezat A. Alaa, 2014, “Simulation Study of Screw Micro Pumps Design and Performance”, M.Sc. thesis, Faculty of Engineering, Port Said University