Experimental Investigation of the Dynamics of Laboratory Simple Surge Tank

Saib A. Yousif
Chemical Engineering Department
College of Engineering
University of Basrah
saib.yowsif@gmail.com

Ali Nasir Kalaf
Chemical Engineering Department
College of Engineering
University of Basrah
alinasserey@yahoo.com

Abstract- **The surge tank is one of important control devices in reducing water Hummer effect on distributed network piping system and hydropower stations. An experimental study was conducted into a simple surge tank of 0.044 m in a diameter with upstream constant head reservoir of a height, 0.881 m and a water transporting pipe of a size 0.0202 m.**

Results indicate that rapid closure of a downstream valve causes under-damped stable oscillation in a surge tank. Experimental response agreed well with theoretical results when friction factor is considered to be variable, but with 85 % increases in settle time and more oscillations when constant friction factor is recognized at initial value before valve closure. Doubling surge tank area does not improve the dynamics properties; otherwise, Thoma area must be avoided for small sizes. Comsol multiphysics software 3.5 is used to deal with the dynamics of the surge tank numerically.

Keywords: Comsol multiphyscs, friction factor, surge tank, valve closure.

I. INTRODUCTION

In hydro-electric power stations and piping networks which are carrying crude oil and other liquids, the flow is reduced suddenly from one steady state to another or is stopped due to unexpected accidents. Rapid rise of the pressure (Water Hammer) through a short time will be established and wave pressure will be generated and moved at wave velocity upstream away from the point of effect, e.g., pump stations, control valves, high elevation area, locations with low static pressures, remote location that are distanced from overhead storage [1].

To reduce this problem and assure protection of piping networks, there appears the need to develop special tools for this purpose incorporated relief valves, surge tanks, control valve, air chamber and bypass on pumps [2].

Kim [3] suggested that a new design of the surge tank could be performed by incorporation of the impulse

response method with the Genetic Algorithm (GA). He concluded that the surge tank design can be made using the pressure-head response at any point along the pipeline system while considering both the security and cost of the system.

Mawash and Gross [4] concluded that the dynamic behavior of pressurized surge tank can be influenced by the liquid height inside the surge tank, the inlet and outlet mass flow rates, the gas pressure in the surge tank, and the liquid kinetic energy.

Borkowski [5] used a precisely designed PI-type controller to control a surge tank water level in a small hydropower plant. A new identification method that uses the step response to identify the parameters of a real system is described. The results of the tests confirmed the stable operation of the controller at the maximum water level fluctuations of ±5 cm during a normal operation.

The Present work aims into investigate the dynamics of simple surge tank experimentally after sudden valve closure and opening locating downstream the surge tank. This study includes theoretical analysis taking into account of the friction factor effects which is considered variable parameter.

II. THEORY

A. Momentum Equation

Figure (1) is schematic diagram of simple surge tank.
Applying Newton second law of movement [6]:
Rate of moment change of fluid= sum of the forces applying on the fluid.

$$-\rho A_1 L \frac{dv_1}{dt} = \rho g A_1 [z \pm (h_f + h_i + h_o + h_v] \quad (1)$$

Where; ρ is water density (kg/m3), A1 is pipe cross sectional area (m2), L is pipe length (m), g is acceleration of gravity, 9.81 (m/s2), z is difference in surge tank height (m), hf is major head loss in pipes (m), hi is enterence head loss (m), ho is exit head loss (m), hv is Velocity head (m) and t is time (s).

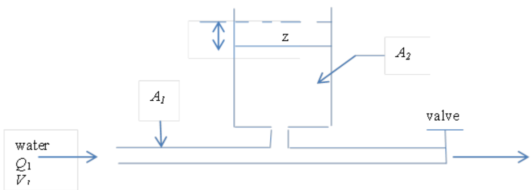

Fig. (1) Simple surge tank

Where,

$$h_f = f \frac{L}{d_1} \frac{v_1^2}{2g}, \quad h_i = k_i \frac{v_1^2}{2g}, \quad h_o = k_o \frac{v_1^2}{2g}, \quad h_v = \frac{v_1^2}{2g}$$

Where; f is friction factor, d_1 is pipe diameter (m), k_i is enterance minor coefficient, k_o is exit minor coefficient and v_1 is water velocity in the pipe (m/s).
Eq. (1) becomes,

$$\frac{L}{g} \frac{dv_1}{dt} + z \pm (h_f + h_i + h_o + h_v] = 0 \quad (2)$$

The Sign (+) represents the case of valve closure and (-) is for valve opening.

***B.* Continuity Equation**

inlet flowrate –outlet flowrate = accumulation

$$Q_1 - Q_V = A_2 \frac{dz}{dt}$$

Where; Q_1 is pipe flowrate (m^3/s), Q_v is flowrate through valve (m^3/s) and A_2 is cross sectional area of surge tank (m^2).

$$\frac{dz}{dt} = \frac{A_1}{A_2} v_1 - \frac{1}{A_2} Q_V \quad (3)$$

Q_V is considered when the valve is opened and neglected in case of valve closure.

$$\frac{dz}{dt} = \frac{A_1}{A_2} v_1 \quad (4)$$

Since water velocity varies through closing and opening the valve, the acceleration and deceleration heads, $\frac{v_1^2}{2g}$, Reynolds No., *Re* and friction factor, *f* will vary as well.

$$Re = \frac{\rho\, v_1\, d_1}{\mu} \quad (5)$$

Where; *Re* is Reynolds No. and μ is water density (kg/m^3)

$$Re = \frac{\rho}{\mu} (\frac{d_2}{d_1})^2 \frac{dz}{dt} \quad (6)$$

The expressions for the friction factor in both laminar and turbulent flow were combined into a single expression: [7]

$$f = 8\, [\, (\frac{8}{Re})^{12} + \frac{1}{(C+D)^{3/4}}]^{1/12} \quad (7)$$

Where,

$$C = [\, 2.457 \ln\{ \frac{1}{\left(\frac{7}{Re}\right)^{0.9} + 0.27\left(\frac{e}{d_1}\right)} \}]^{16} \quad (8)$$

Where; e is pipe roughness.

$$D = \left(\frac{37{,}530}{Re}\right)^{16} \quad (9)$$

In case of valve opening, Reynolds No. will be,

$$Re = \frac{\rho\, d_1}{\mu} [\, (\frac{d_2}{d_1})^2 \frac{dz}{dt} + \frac{Q_v}{A_2}] \quad (10)$$

The initial conditions to solve Eqs.(2) and (4):

$$t = 0\,, z = z_i \;\; and \;\; v_1 = v_i \quad (11)$$

Where; z_i is initial height (m) and v_i is initial velocity (m/s)..

Comsol Multiphysics software 3.5 [8] which based on finite element method was used to solve non-linear differential equations: 2, 4, 5, 7, 8, 9 and 11 numerically. While the graphs are performed with Microsoft excel.

C. Dynamics of Surge Tank without Friction Losses

This case is studed as reference because water head in the surge tank will be maximum when the valve is closed rapidly and minimum when the valve is opened [6].

Eq. (2) becomes,

$$\frac{L}{g} \frac{dv}{dt} + z = 0 \quad (12)$$

Eq.(4) is derived and substituted in Eq.(12),

$$\frac{d^2 z}{dt^2} + \frac{g}{L} (\frac{d_1}{d_2}^2) z = 0 \quad (13)$$

Solving Eq. (13),

$$z = c_1 \cos\sqrt{\frac{gA_1}{LA_2}}\, t + c_2 \sin\sqrt{\frac{gA_1}{LA_2}}\, t \quad (14)$$

c_1 and c_2 are found by using the following initial conditions,

$$t = 0, \quad z = 0, \quad \frac{dz}{dt} = \frac{Q_o}{A_2} \quad (15)$$

The analytical solution to Eq.(14) is,

$$z = Q_o \sqrt{\frac{L}{gA_1A_2}} \sin\sqrt{\frac{gA_1}{LA_2}}\, t \quad (16)$$

The maximum water level in the surge tank is,

$$z_{max} = Q_o \sqrt{\frac{L}{gA_1A_2}} \quad (17)$$

III. EXPERIMENTAL WORK AND PROCEDURE

The experiments were carried out using surge tank and water hummer apparatus supplied by Armfield Co., UK, [9] as shown in Fig. (2). Water is drawn from a hydraulic tank by a centrifugal pump and pumped through feed pipe to a constant head tank of diameter 0.044 m and constant water level, 0.881 m. There is

manual control valve on the feed line to regulate the flow. The constant head tank is supplied with a central pipe for receiving overflow water which returns to hydraulic tank. The water flows from the constant head tank through stainless steel pipe of diameter 0.0202 m and length 3 m. At the end of the pipe stands a transparent simple surge tank of diameter 0.044 m and manufactured from Pyrex. Two valves are installed downstream of the surge tank, manual gate valve and manual outlet control valve.

The flowrate is measured by collecting a certain volume of water in a graduated cylinder located at the side of hydraulic tank at fixed time.

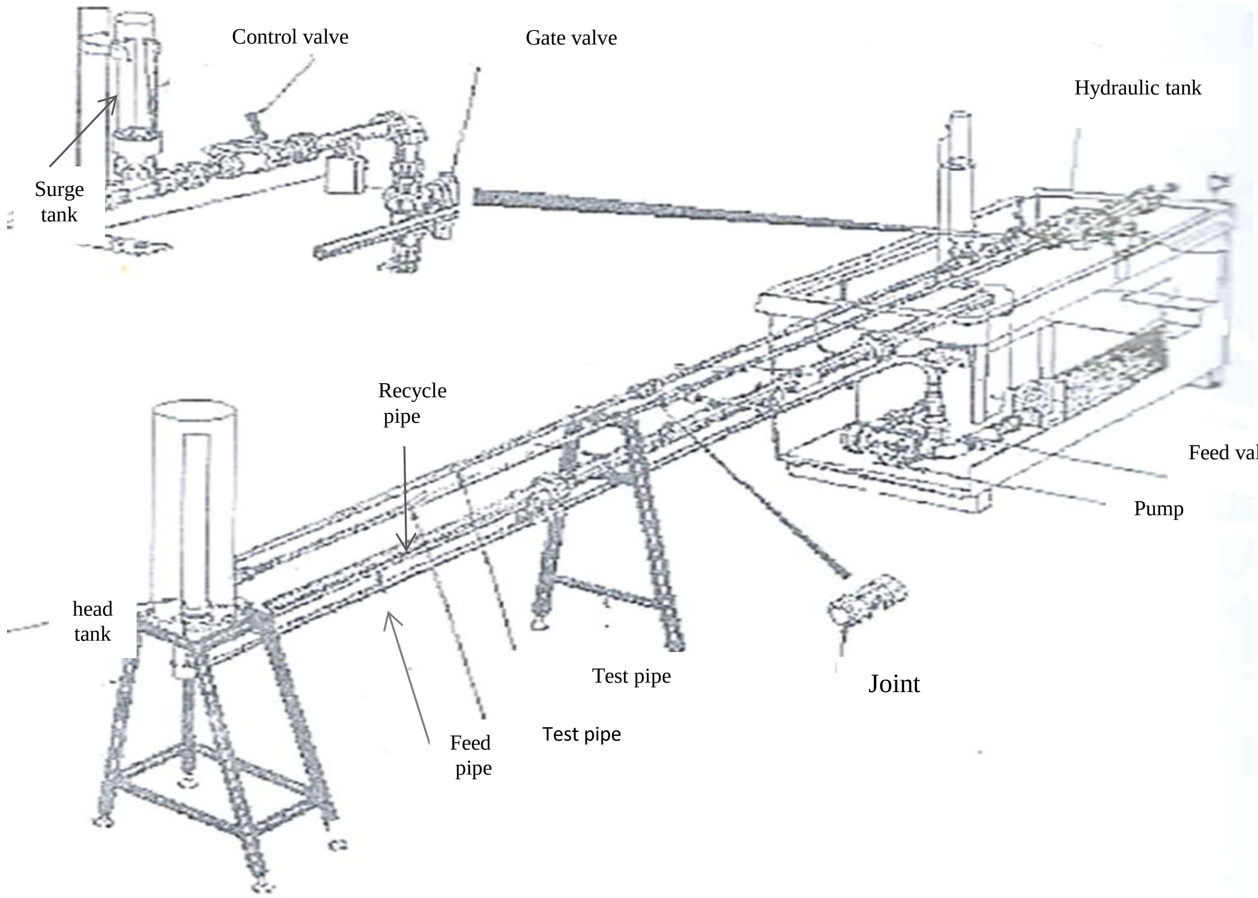

Fig. (2) Assembly of surge tank apparatus

The pump will be switched on with the feed valve and the gate valves are opened till the water returns to the hydraulic tank. After the system is steady the gate valve is closed rapidly and the level of the surge tank will be measured with time record until the level comes back to the steady again. To measure level variation of the surge tank after valve opening, the gate valve is closed while outlet valve is opened for a while. After that the gate valve is opened and the level will be measured with time.

IV. RESULTS AND DISCUSSION

A. Rapid Valve Closure

Fig. (3) shows the experimental variation of the difference of water level of the surge tank with time after rapid closure of the manual gate valve. It is obvious that the oscillation is stable and under damped. When the valve is closed at t=0, the water in the surge tank begins to rise from initial level, 0.086 m exceeding the level of constant head tank, 0.75 m and reaching a maximum 0.0952 m (0.845 m, height) after 4 sec which is less than flooding condition, 0.881 m. The rise of water is due to the conversion of kinetic energy to the wave pressure in the pipe joining constant head tank and the surge tank. These waves move inside surge tank instead of moving in the pipe and pushing water in the tank. After that the level begins to slow down to a level less than that of constant head tank. The level will continue oscillating with attenuated amplitude. Finally, the level will settle to its initial value. It was seen that the level reaches 1/10 of the maximum value, 0.759 m after 26 sec.

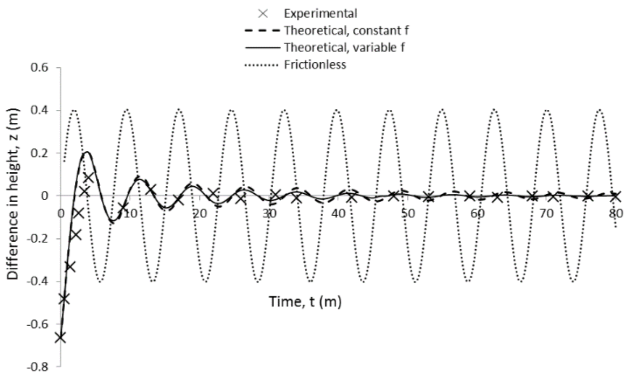

Fig.(3) Difference in water level vs time

The dynamics of the surge tank was studied theoretically by assuming the system is frictionless which performs inviscid ideal fluid. Eq. (16) is solved and the results are plotted in Fig. (3). On comparison with experimental results, the oscillation was found sinusoidal and stable with higher amplitude, 0.4028 m (1.153 m, height) causing flooding to occur. The period time is found to be 7.5 sec.

Another theoretical study was carried out in which friction losses, (major and minor) are incorporated. Major loss occurs through the pipe while minor losses are in entrance, exit and deceleration head. Eqs. (2), (4), (6), (7) and (8) are solved numerically using Comsol Multiphysics

3.5 software with the aid of Microsoft Excel to analyze and plot the results. The time interval chosen is 0.1 sec and the surge tank is assumed one directional divided into 30 finite elements or 31 nodes. The results are plotted in Fig. (3) and the dynamics characteristics are listed in table (1). The amplitude ratio, period, time to reach 1/10 maximum amplitude and No. of periods, 0.37, 7, 30 sec and 4.5, respectively are in a good agreement with experimental results.

The variation in maximum amplitude, e.g. 0.203 compared to experimental value, 0.083 is due to the assumption of rigid properties of the surge tank in theoretical model. While pressure wave which causes maximum amplitude depends mainly on elastic properties, Young's modulus of elastisity of tank wall and bulk modulus of water.

In previous studies [2, 8], friction factor was assumed constant after valve closure. In present work, this case is studied and the dynamics is predicted and plotted in Fig. (3). It was found that the time to reach 1/10 max. amplitude is 48 sec which is 60 % higher than that for variable friction factor, 30 sec and 85 % higher when compared with experimental results. This is due to the damping effect of viscous resistance which increases as the water velocity slows down with time. Number of oscillations is higher as well.

The velocity of the water in the test pipe varies throughout the run as illustrated in Fig. (4). The initial velocity is 1.59 m/s at time, t=0, then it begins to oscillate with damping amplitude. Reynolds No. and friction factor are considered varied as shown in Figs. (5). At the beginning before valve closure, the flow is turbulent, *Re* and *f* are 32118 and 0.02307, respectively. After closing the valve, Reynolds No. reduces gradually from turbulent to transient to laminar while friction factor increases from 0.02306 to 0.054 when the level is stabilized.

B. Effect of the Area on the Level Stability

Two areas of the surge tank are chosen, e.g., 0.507e-3 m^2 and 3.167e-3 m^2 which correspond to diameters 0.0254 m (1 inch) and 0.0635 m (2.5 inch) and the dynamics are studied and compared theoretically. The results are plotted in Fig. (6). It is seen that for all dimensions the level is stable and under damped. When the area is doubled there is relative improvement in the overshoot but on the other hand the fixed cost will be magnified. When the area is reduced to less than half, flooding will occur due to increase the overshoot. The small area is still less than Thoma area, e.g., 0.374e-3 m^2 which makes the system unstable [10].

Table (1) Dynamics characteristics of simple surge tank

Experimental and Theoretical flow	Max. amplitude, m m	Amplitude ratio	Period, sec	Time of 1/10 max. amplitude, sec	No. of periods to 1/10 of max. amplitude	Oscillation type
Experimental	0.083	0.35	9	26	3.3	Under damped
Theoretical, variable f	0.203	0.367	7	30	4.5	Under damped
Frictionless	0.4	1	7.5	------	-------	oscillatory
Theoretical, constant f	0.204	0.42	7	48	6.5	Under damped

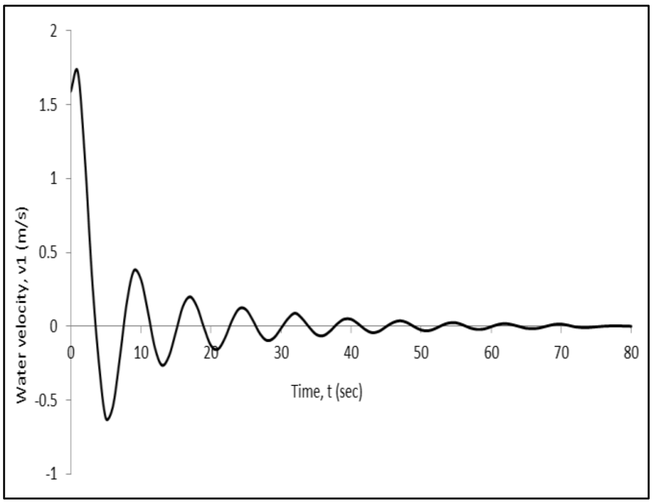

Fig. (4) Water velocity in the test pipe vs time

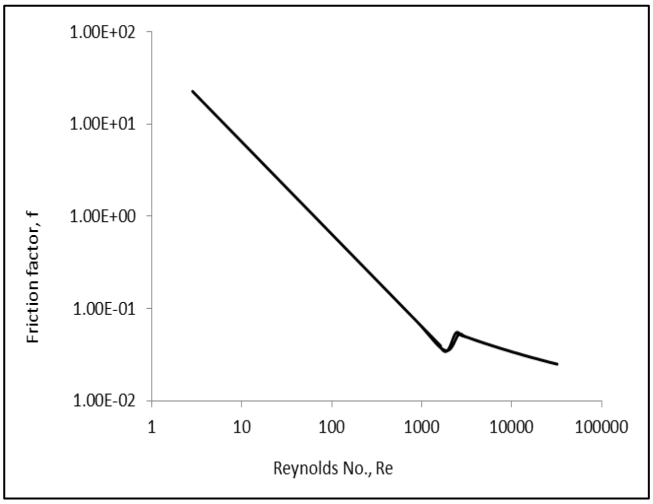

Fig. (5) Friction factor vs Reynolds No.

A. Rapid valve opening

This case is studied to simulate surge tanks in hydro-electrical power stations where the load on turbine is considered variable. This will cause to limit entering water to the turbine. Fig. (7) Illustrates experimental dropping of water level in the surge tank after sudden opening of the gate valve.

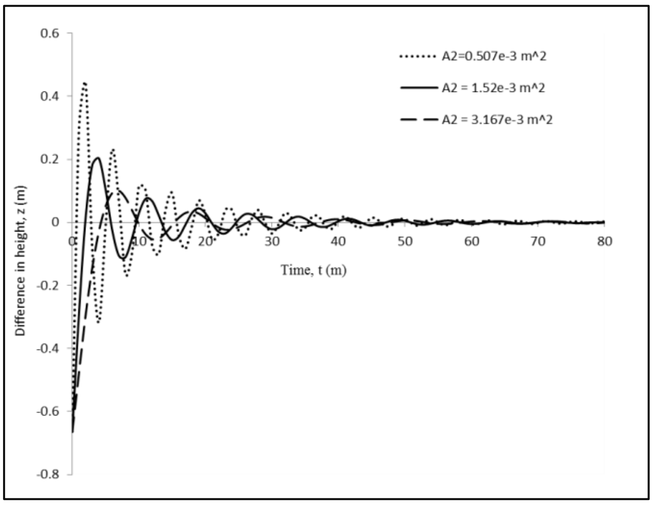

Fig. (6) Difference in water level vs time at different areas of surge tank

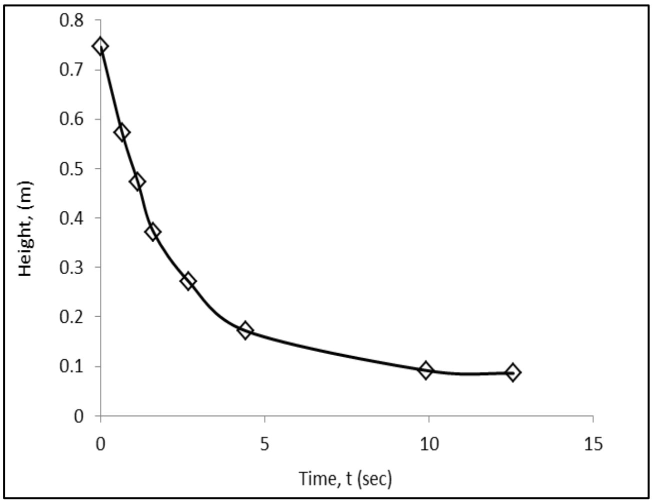

Fig.(7) Water level vs time for the surge tank

V. CONCLUSION

This study focuses on the analyze of the surge wave height within the simple surge tank and the time of dissipation. The oscillation of tank level is found stable underdamped after rapid closing of the valve. The experiments are agreed well with the theoretical approach when the friction loss is included as dynamic parameter and with more oscillation and much settling time when the friction loss is fixed. Increasing the area of the surge tank had no significant effect on the level stability. It is necessary to avoid Thoma's area when one think to reduce surge tank area.

VI. REFERENCES

1. M.C. Friedman, "Verification and control of low pressure transients in distributed system", Proc. 18th Annual ASDWA Conf. Boston, 2003.
2. J. F. Douglas, M. Gasiorek and J. A. Swaffield, "Fluid Mechanics", 3rd ed., Longman, 1998
3. S. H. Kim, (2010). "Design of surge tank for water supply systems using the impulse response method with the GA algorithm", Journal of Mechanical Science and Technology Vol. 24, No. 2, pp. 629-636.
4. Mawash, P. R. and Gross, R. H. (2001). "Understanding the nonlinear dynamics of liquid flow with surge tanks", International Journal of Mechanical Engineering Education, Vol. 29, No. 1, pp. 53-66.
5. D. Borkowski, (2016). "Water level control of a small hydropower plant with a surge tank", Journal of Hydraulic Research 55(2):1-8.
6. M. H. Chaudhry, "Applied Hydraulic Transient", Litton Educational Publishing", 1979.
7. R. Darby, "Chemical Engineering Fluid Mechanics", 2nd ed., Marcel Dekker, 2001
8. COMSOL Inc. "Chemical Engineering Module, Model Library", Version 3.5a, pp. 613, 2008
9. Instruction manual. "Pipe surge and water hammer apparatus", Armfield, C7-00, Issue 11.1988
10. C. Jaeger
11. , " A review of surge tank stability criteria", Journal of Basic Engineering, ASME, Dec., pp. 765-775, 1960.

VII. . BIOGRAPHIES

Saib A. Yousif received the B.Sc. degree in Chemical Engineering from Dept. of Chemical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq in 1981. He received the M.Sc. degree in "Chemical Engineering" from University of Baghdad, in 1985. He received the Ph.D. degree in "Mechanical Engineering" from University of Basrah, Basrah, Iraq in 2014. He is working as lecturer in the Dept. of Chemical Engineering, College of Engineering, University of Basrah, Basrah, Iraq. His research interest includes; heat transfer, mass transfer, waste treatment, fluid flow and pollution