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Simplified Correlation Equations of Heat Transfer Coefficient During Phase Change Flow Inside Tubes Filled with Porous Media

M. Hammad
Prof. of Mechanical Engineering,
University of Jordan, Jordan,
Tel/fax: +962/6-5238783,
hammad@ju.edu.jo

M. Tarawneh
The Hashemite University,
Zarka, Jordan ,
mohammad.tarawneh@hu.edu.jo

A. Al-Shqirate
Al-Shoubak University College,
Al-Balqa Applied University, Al-Salt, Jordan,
Abedalrzaq_alshqirate@yahoo.com

Abstract
In this work an easy to use, simple and direct equations were formulated and tested. Heat transfer coefficients of phase change fluid flow were examined in this work. The considered fluid flow encountered convection heat flux inside rigid tubes filled with porous media. During the flow, phase change was assumed. Experimental work was conducted using Carbon dioxide as fluid.
An analytical method using exponential non dimensional analysis was used. The Buckingham π theorem and method of indices was used to obtain simplified formula for the convection heat transfer coefficient and for the Nusselt number.
Two different correlations can be extracted from this formula; one for the evaporation process and the other for the condensation process.
As a case study, carbon dioxide was used. Resulted values were compared to the experimental values for validation purposes. Results also were compared to published values and found in the same range of uncertainty and exactness.
The formulae obtained can be used to calculate the mean heat transfer coefficients, (h^{-}_{corr}) and heat flux. Heat flux is the catalyst for phase change. Enhancement in heat transfer by increasing heat flux was due to the existence of the porous media inside the tube.
Better heat exchanger design as well as better condensers and evaporators will result. Better energy use and higher effectiveness factors may result by using more simple and accurate equations.
Keywords: Porous Media, Heat Transfer, Two Phase Flow, Change of Phase, Refrigeration, Carbon Dioxide.

Introduction
Heat transfer and fluid flow inside tubes have many applications, such as: heat exchangers, condensers, evaporators and boilers. Using porous media inside tubes enhances radial heat flux and increases heat transfer coefficients.
Convection heat transfer for a phase change flow inside tubes was studied in the literature. Mini and micro-tubes were used. Many correlations for mean Nusselt number ($\overline{Nu}$) and mean heat transfer coefficient ($\bar{h}$) were obtained. Both $\overline{Nu}$ and $\bar{h}$ were calculated using the analytical correlation or using the experimental results for the purpose of validation. Bejan (1993) and Thome (2005) are good examples for literature work in this field. Both of them included a comprehensive review of boiling flow inside tubes heat transfer analysis.

Nield and Bejan (2006) discussed flow and convection heat transfer in porous media for single phase fluid. Numerical solutions were implemented for cylindrical and annular configurations. Bergines et al. (2005) and Jiang et al. (2004) studied experimentally phase change processes for flow inside porous tubes. The first work used water and steam flow, while the second used carbon dioxide (CO_2).
Al-Tarawneh (2007), Al Tarawneh, (2011) and Tarawneh, (2011), investigated CO_2 flow inside tubes filled with porous media. The authors used the step – by step dimensional analysis for the mean value of the Nusselt number, ($\overline{Nu}$), and formulated the following equations:
For evaporation:

$$\overline{Nu} = 1.27 * 10^{-4} \left[(Re_{De})^{2.9762} \left(\frac{u_m^2}{h_{fg}}\right)^{-2.0133}, (Pr)^{-1.7603} (Ga)^{-1.4656} (Br)^{1.0405} (Bo)^{1.1655} \left(\frac{L_e}{D_e}\right)^{-0.8327} (Eu)^{-0.0182} (Da)^{0.4011}\right] \quad (1)$$

For condensation:

$$\overline{Nu} = 1.8 * 10^{(9)} \left[(Re_{,De})^{-0.2574} \left(\frac{u_m^2}{h_{fg}}\right)^{2.2563}, (Pr)^{-0.9698} (Ga)^{0.1793} (Br)^{-0.0033} (Bo)^{0.0598} \left(\frac{L_c}{D_e}\right)^{-0.637} (Eu)^{1.6177} (Da)^{0.0061} \quad (2)$$

Porosity in his work ranged from 39% up to 45%. Buckingham, π, pi theory method for non dimensional analysis was used to formulate the previous correlation equations.
The phase change flow combined by non dimensional analysis appeared in some other works, such as Hammad et al, (2011).

Nomenclature

Bo	Bond number
Br	Brinkman number: characterizing viscous dissipation
C_0,C_1	Constants
C_{pa}	Apparent specific heat (kJ/kg K)
C_{pm}	Mean specific heat (kJ/kg K)
C_{ps}	Specific heat of the solid material (kJ/kg K)
CO_2, *(R744)*	Carbon Dioxide
Da	Darcy number which represent dimensionless pressure drop
DAS	Data acquisition system
D_{eff}	Effective diameter (m)
D_i	Internal diameter (m)
Eu	Euler number
F	Some function
Ga	Galilio number: the ratio between the gravitational force (buoyancy force) and viscous force.
$h_{fg, eff}$	Effective latent heat of vaporization (kJ/kg)
$h_{g, Pin}$	Saturated vapor specific enthalpy at phase change inlet pressure (kJ/kg)
$h_{f, Pout}$	Saturated liquid specific enthalpy at phase change outlet pressure (kJ/kg)
$\overline{h}$	Mean heat transfer coefficient (W / m ^{2} .K)
$\overline{h}_{corr}$	Correlated heat transfer coefficient(W / m ^{2}.K)
$\overline{h}_{exp}$	Experimental heat transfer coefficient (W/m ^{2} .K)
Ja	Jacobs number
K	Permeability (m ^{2})
K_a	Apparent thermal conductivity (W/m.K)
K_{cop}	Copper thermal conductivity (W/m. K)
K_m	Mean thermal conductivity (W/m. K)
K_s	Thermal conductivity of the solid material
W_j	The uncertainty in each basic measured quantity
W_r	The uncertainty in the results

Greek symbols

α	Thermal diffusivity
γ	Viscosity increase factor
ΔT_m	Mean surface temperature difference (^{o}C)
ΔT_{in}	Temperature difference between refrigerant inlet saturation temperature and surface temperature (^{o}C)
ΔT_{out}	Temperature difference between refrigerant outlet saturation temperature and surface temperature (^{o}C)
μ	
μ_a	Apparent dynamic viscosity (Pa.s)
μ_m	Mean dynamic viscosity (Pa.s)
ε	Porosity
σ	Surface tension (N/m)
ρ_g	Gas state density (kg/m^3)
ρ_f	Liquid state density (kg/m^3)
ρ_m	Mean density (kg/m^3)
Φ	Non dimensional number
$\dot{m}_{CO2}$	Mass flow rate of carbon dioxide (kg/s)
$\dot{Q}_{CO2}$	Total heat transfer rate rejected from carbon dioxide gas (watt)
ΔT_{lm}	Logarithmic mean temperature difference (^{o}C)
$\dot{V}_{CO2}$	Volumetric flow rate (m^3/s)
$\frac{\partial R}{\partial X_j}$	Sensitivity of the measured quantities

Subscripts

a	Apparent
b	Barometric
c	Condensation

	(W/m. K)		
L_c	Condensation region length (m)	*cop*	Copper
L_e	Evaporation region length (m)	*corr*	Correlated (predicted)
$\overline{Nu}$	Mean Nusselt number	*e*	Evaporation
P_{in}	Test section inlet pressure (kPa)	*eff*	Effective
P_{out}	Test section outlet pressure (kPa)	*exp*	Experimental
P_{is}	Saturation pressure (kPa)	*f*	Liquid
P_b	Barometric pressure (kPa)	*g*	Gas
Pr	Prandtl number	*i*	Internal
R_i	Thermal resistance, (W/Km^2)	*in*	Inlet
r_i	Tube internal radius (m)	*lm*	Logarithmic
r_o	Tube external radius (m)	*m*	Mean value
Re_{Deff}	Reynolds number based on effective diameter	o	External
$T_{sat,in}$	Condenser inlet saturation temperature (^{o}C)	out	Outlet
$T_{sat,out}$	Condenser outlet saturation temperature (^{o}C)	s	Solid
T_{surf}	Measured outer surface temperature (^{o}C)	surf	Surface
U_m	Mean velocity (m/s)	Super scripts	
We	Weber number	m,n,l	Constants

Experimental Work

The test apparatus used in this study and its main components are shown in Fig.1. This experimental set-up consists of:

1. The pressurized carbon dioxide gas cylinder as a main source of carbon dioxide gas, 2- high pressure regulating valve with built-in gas cylinder pressure gauges, 3- chest freezer used as environment to cool, condense and sub cool the carbon dioxide gas flowing inside the condenser test section by natural convection, 4- the porous condenser, 5- high pressure cut-off and isolating valves, 6- pressure gauges, 7- sight glasses, 8- the porous evaporator. 9- data acquisition System (DAS), 10- volume flow meter for measuring the mass flow rate of the gas.

The tube outside surface temperature was measured at 28 points. These points are at longitudinal distances from each others. K-type thermocouples were used. They were connected to a module of (32 channels), which is in turn plugged in the Data Acquisition System (DAS) of model SCXI-1000. The well-known (LAB VIEW) software was used for processing the signals of the thermocouples and for transforming them into temperature readings on the screen of a personal computer. For each experimental test run, the variation of the temperature with time was monitored. The temperature readings were repeatedly recorded for a certain period until the steady state conditions were achieved.

The experimental conditions used in this study are listed in Table 1.

Forty eight different tests of different parameters were carried out within the ranges shown by Table 1.

Table 1. Experimental domain

Test sections	Condenser section (Di=1.73 cm)	Evaporator section (Di=1.73 cm)
Process	Condensation inside a chest freezer of -28 ^{o}C	Evaporation in still room temperature air
Working fluid	CO_2	CO_2
Mean diameter of the particles of the sand.	5.15 mm, 2.03 mm, 3.18 mm	5.15 mm, 2.03 mm, 3.18 mm
Permeability(κ) (m^2)	$4.65*10^{-12}$, $5.7*10^{-12}$, $8.2*10^{-12}$	$4.65*10^{-12}$, $5.7*10^{-12}$, $8.2*10^{-12}$
Porosity	39.8%, 43%, 44.5%	39.8%, 43%, 44.5%
Test section total length (m)	8.55 m	6.05 m
Test section inlet pressure (kPa)	3450, 3700, 4000, 4300	3700, 4000, 4300, 4600
Saturation temperature (^{o}C)	-0.47, 2.27, 5.30, 8.25	2.27, 5.30, 8.25, 1.087
Volume flow rate (l / min)	3, 4, 5, 6	4, 5, 6, 7

The apparent thermal conductivity and heat capacity of the porous bed comes as a result of

the solid material effect. Both can be given by the following equations: Hammad, et al, (2011).

$$K_a = \varepsilon K_m + (1-\varepsilon) K_s \quad (3)$$

$$C_{pa} = \varepsilon C_{pm} + (1-\varepsilon) C_{ps} \quad (4)$$

While the apparent viscosity which was increased due to the increase of the solid area

contacted while flowing in the stationary porous media. It can

be calculated by the following relation:

$$\mu_a = \gamma \mu \quad (5)$$

Where $\gamma > 1$ and equals $[1+ (1-\varepsilon) D/d]$. It can be called viscosity increase factor.

The apparent values replaced the mean values used for the calculations of the physical properties and flow quantities used to calculate the mean heat transfer coefficients.

The thermal conductivity of the sand was found experimentally in the lab. The apparatus (B480 Thermal Conductivity of Building Materials Unit), was used for this purpose.

The pressure drop and the convection heat transfer coefficient during the processes were calculated using the collected by the Data Acquisition System, (DAS).

The experiments were carried out by condensing the CO_2 gas inside the tube coiled in the the constant temperature space of the chest freezer, then the liquid is evaporated inside the pipe upon its exit from the chest freezer to the constant room temperature laboratory space. The outside surface temperatures of the condenser and the evaporator tubes were measured and recorded. The inlet and the outlet pressures and gas flow rates for each test were also measured and recorded.

Figure 2 shows a typical longitudinal distribution of the outer surface temperatures of a typical condensation experiment. The Figure shows a gas cooling part, a liquid sub-cooling part and in between is the condensation part. The three lines have different slopes. This study is concerned only with the middle line which shows the process of condensation only. From the Figure, the condensation tube length, (L), can easily be measured.

Latent heat released by the gas as it condenses will be transferred radial wise by: forced convection, conduction and free convection through the tube to the chest freezer.

Heat transfer balance equations are as follows:

$$\dot{Q}_{CO2} = \dot{m}_{CO2} * h_{fg,\,eff} = 2\pi L\,(\Delta T_{lm})/(C_o + C_1 R_i) \quad (6)$$

Where thermal resistance of the tube wall was neglected.

Where the logarithmic mean temperature difference equals:

$$\Delta T_{lm} = (\Delta T_i - \Delta T_o) / \ln(\Delta T_i / \Delta T_o) \quad (7)$$

Where: $\Delta T_o = T_{sat,\,out} - T_{sur}$ and

$\Delta T_i = T_{sat,\,in} - T_{sur}$

and, $T_{sat,out}$, $T_{sat,in}$ are the outlet saturation temperature and inlet saturation temperature of the condensation part of the test tube. T_{sur} is the measured tube surface temperature.

$C_o = (\ln r_o/r_i)/K_c$, where K_c is the copper thermal conductivity, and $C_1 = 1/r_i$, where r_o and r_i are tube outside radius and inside radius, respectively.

$$h_{fg,\,eff} = h_{g,\,Pin} - h_{f,\,Pout} \quad (8)$$

Where: $h_{g,\,Pin}$ = Saturated vapor specific enthalpy at phase change inlet pressure (kJ/kg).

$h_{f,\,Pout}$ = Saturated liquid specific enthalpy at phase change outlet pressure (kJ/kg).

The experimental mean heat transfer coefficient will be,

$$\bar{h}_{exp} = 1/Ri \quad (9)$$

The values of $\bar{h}_{exp}$ were tabulated and used in the analysis.

Uncertainty Analysis for Experimental Work

The uncertainty in the experimental work was calculated using the known, following Kline and McClintock relation:

$$W_r = [(\frac{\partial R}{\partial X_1} W_{X1})^2 + (\frac{\partial R}{\partial X_2} W_{X2})^2 + \ldots\ldots\ldots + (\frac{\partial R}{\partial X_j} W_{Xj})^2]^{1/2} \quad (10)$$

Where; W_r is the uncertainty in the results, and W_j is the uncertainty in each basic measured quantity.

The partial derivatives $\frac{\partial R}{\partial X_j}$ are the sensitivities of the measured quantities.

The measured quantities were: tube outsurface temperatures, (T_{wo}); saturation pressure, (Pis); room barometric pressure, (Pb) and the volume flow rate, ($\dot{V}_{co2}$).

The uncertainty can be expressed as:

$W_{h\exp}$ =

$$[(\frac{\partial \overline{h}\exp}{\partial Two} W_{T_{surf}})^2 + (\frac{\partial \overline{h}\exp}{\partial Pis} W_{P_g})^2 + (\frac{\partial \overline{h}\exp}{\partial P_b} W_{P_b})^2 + (\frac{\partial \overline{h}\exp}{\partial \dot{V}co2} W_{\dot{V}})^2]^{1/2} \quad (11)$$

A list of the values of uncertainties and sensitivities required for Eqn. (9), for a typical condensation test is shown in Table 2..

Table 2. All the values of uncertainties and sensitivities required for Eqn. (11).

Variable	Value	Variable	Value
$\frac{\partial \overline{h}\exp}{\partial Two}$	1.31	$\frac{\partial \overline{h}\exp}{\partial P_b}$	0.0014
$(W_{T_{wo}})$	± 1.0 °C	(W_{P_b})	± 0.25 mbar
$\frac{\partial \overline{h}\exp}{\partial P_{is}}$	0.1173	$\frac{\partial \overline{h}\exp}{\partial \dot{V}co2}$	0.0587
(W_{P_g})	± 0.5 bar	$(W_{\dot{V}})$	± 0.5 liter/min

Calculations gave the following value:

$W\,\overline{h}_{\exp} = \pm\ 1.31$ W/ m^2.K, which is around 1% of the original value.

In the same way, the uncertainty for the evaporation process can be calculated.

Analytical Study

The variables affecting the convection heat flux in the processes under consideration were gathered in one equation. The mean values for complete evaporation and complete condensation processes were used. Heat flux in both the sub-cooled and the superheated regions was not considered in this work.

The variables totaled twelve. The following equation represents the relation between all variables, whether dependent or independent

$$f(\overline{h}, \rho_m, k_a, h_{fg}, Cp, \Delta T_m, \mu_a, \sigma, U_m, (\rho_l - \rho_v), D, \varepsilon) = 0 \quad (12)$$

The basic number of dimensions contained by the variables is four: mass, kg., length, m, time, s and temperature, k. This implies that the suitable number of non dimensional quantities required to represent equation 12 is eight. Each quantity may be called Pi, (Π), Crowe, et al, (2001).

The following non-dimensional Pis were formulated using the exponential method for dimensional analysis:

1- The porosity,
$\Pi_1 = \varepsilon$

2- Reynolds number,
$\Pi_2 = Re_D = \rho_m U_m D/\mu_a$

3- Prandtl number,
$\Pi_3 = Pr = Cp_a \mu_a / k_a$

4- $\Pi_4 = U_m \mu_a / D h_{fg} \rho_m$

5- Weber number,
$\Pi_5 = We = \rho_m U^2_m D/\sigma$

6- $\Pi_6 = (\rho_l - \rho_v)/\rho_m$

7- Jacobs number,
$\Pi_7 = Ja = Cp_a \Delta T_m / h_{fg}$

8- $\Pi_8 = \overline{h} U_m / \rho_m h_{fg} Cp_a$

The main variable is $\overline{h}$. This variable is included within Π_8 this will give the following relation:

$$\Pi_8 = f(\Pi_1, \Pi_2, \Pi_3. \Pi_4, \Pi_5, \Pi_6, \Pi_7) \quad (13)$$

To simplify this equation:

$(\Pi_2 * \Pi_3 * \Pi_4) / \Pi_7 = U^2_m \mu_m / \Delta T_m k_m = Br$

$\Pi_5 * \Pi_6 = (\rho_l - \rho_v) U_m^2 D_i / \sigma_m$ = modified We

Thus: $\Pi_8 = f(\varepsilon, Br, We)$ (14)

This is a very important non dimensional number and up to the knowledge of the authors, it was not mentioned in the literature and not used before. This new number, (Nn, which is Π_8) Will be given the symbol, Φ, and thus:

$\Phi = (\overline{h} U_m / \rho_m Cp_a h_{fg})$.

The importance of this number emanates from that it contains the main dependent variable which is the mean convection heat transfer coefficient, ($\overline{h}$), and relates the convection heat flux to the stored quantities of heat as sensible heat presented by the mean specific heat,(Cp_m) and latent heat, (h_{fg}). This number can be compared to the diffusivity of the conduction heat flux, ($\alpha = k/\rho Cp$) which relates conduction heat flux, (k) to stored heat, (Cp). This number may represent the diffusivity of the convection heat flux in the case of phase change flow,and can be put in the form, ($\alpha_{conv} = \overline{h} U_m / \rho_m Cp_a h_{fg}$).

Equation 14 can be written in the form:

$$\Phi = C (Br_m)^m (We_m)^n (\varepsilon)^l \quad (15)$$

Empirical Correlations

The aim of this work is to formulate simple correlations that help in calculating the mean heat transfer coefficients in the case of phase change for flow in porous media inside tubes. Equation 15 can be written as:

$$\bar{h}\ U_m/\ \rho_m\ Cp_a\ h_{fg}\ = C\ [U_m^2\ \mu_a/(k_m\ \Delta T_m)]^m\ [\ (\rho_l-\rho_v)U_m^2\ D/\ \sigma]^n\ (\varepsilon)^l \qquad (16)$$

This correlation can be used to calculate the mean value of heat transfer
coefficients if the constants: C, m, n and l are known. The values of these constants depend on the kind of the flowing fluid, and can be calculated using experimental results. The mean value of heat transfer coefficient calculated in this way will be called the correlation resulted value, ($\bar{h}_{corr}$).

In this work, the experimental part was carried out using carbon dioxide.

From Eqn. (16), the mean heat transfer coefficient ($\bar{h}_{corr}$) formula will be:

$$\bar{h}_{corr} = C\ (\rho_m\ Cp_a\ h_{fg}\ /\ U_m\ )\ \ [U_m^2\ \mu_a/(k_a\ \Delta T_m)]^m\ [\ (\rho_l-\rho_v)U_m^2\ D/\ \sigma]^n(\varepsilon)^l \qquad (17)$$

Constants C, m, n and l were evaluated for CO_2 using experimental results for both cases: evaporation and condensation. The values of the constants are shown in Table 3.

Table 3. Constants of Eqn. (17) for CO_2.

Constant	C	m	n	L
For evaporation	3.3 * 10^{16}	2.6	-0.12	-0.43
For condensation	1.577* 10^{-4}	0.435	0.053	-4.84

This gave the two following equations:

$$\Phi\ = 3.3*10^{16}\ (Br_{m})^{2.6}\ (We_{m})^{-0.12}\ (\varepsilon)^{-0.43} \quad \text{for evaporation} \qquad (18)$$

and

$$\Phi = 1.577*10^{-4}\ (Br_{m})^{0.435}\ (We_{m})^{0.053}(\varepsilon)^{-4.84} \quad \text{for condensation.} \qquad (19)$$

Analysis

A comparison between the mean experimental heat transfer coefficients, ($\bar{h}$ exp), of this work and those calculated using the correlation equations obtained from this work, ($\bar{h}$ corr) was conducted.

For evaporation, the comparison is illustrated in Fig. 3. It is clear that some predicted values of

W $\bar{h}$ corr = $\pm$ 1.24 W/m2.K. Comparison of the results obtained by Eqn. (19) for $\bar{h}_{corr}$ with results of other works was carried out. Different published works showed different The comparison is exhibited in Fig. 8, which correlations for the mean convection heat transfer coefficient during flow in porous media inside tubes while condensing CO2 (Al Tarawneh (2008) and Jiang et al (2004)).

$\bar{h}$ corr gave underprediction results. Some other results show best fit with the experimental results. Considering the whole points of the Figure, a mean factor of conformity,($\bar{h}$ exp/ $\bar{h}$ corr), of 1.3 is obtained. This sheds light on the relation between the error, in predicted results and those in the experimental ones. The relation can be put in the following form:

$$\Delta\ \bar{h}\ \text{corr} = 0.77\ \Delta\ \bar{h}\ \text{exp.}$$

Comparison of the results obtained by Eqn (18) for $\bar{h}$ corr with results of other works was curried out (Al Tarawneh (2008) and Thome (2005)). Different published works showed different correlations for the mean convection heat transfer coefficient during flow in porous media inside tubes while evaporating CO2.

The comparison is exhibited in Fig. 4, which shows an overprediction of Al Tarawnah results, and at the same time an underprediction of Chang model (Al Tarawneh (2008) and Chang and Pega (2005)). This underprediction is attributed to the fact that the model was used for empty microchannel tubes.

Figures 5 and 6 explain the effects of: Br, We and ε on Φ and thereby their effects on the mean heat transfer coefficient of the evaporating flow inside pipes full of porous media. The relation illustrated in both Figures is described by Eqn. (18).

Due to the positive value of the exponent m in Eqn (18) and to the negative value of both exponents: n and l in the same equation, it is clear that as Br increases Φ increases and as We or ε increases Φ decreases. It is clear that $\bar{h}$ corr follows Φ in behaviour.

For condensation, the comparisons are illustrated in Figs. 7 to 10. Figure 7 compares the $\bar{h}$ exp with that predicted by Eqn. (19). Point distribution show s a good balance and a good fit with a conformity factor, ($\bar{h}$ exp / $\bar{h}$ corr), of around 1.05. This sheds light on the relation between the error, in predicted results and those in the experimental ones. The relation can be put in the following form:

$$\Delta\ \bar{h}\ \text{corr} = 0.95\ \ \bar{h}\ \text{exp.}$$

For the example calculated in the experimental
error analysis, the error in calculating $\bar{h}$ corr can be predicted to be aroun 1%. Jiang et al. This underprediction is attributed to the fact that experimental results were used in Jiang figures. Jiang et al (2004). shows a good conformity with the results of Al Tarawneh (2008) and at the same time an underprediction of the experimental results of

Figures 9 and 10 explain the effects of: Br, We and ε on Φ and thereby their effects on the mean heat transfer coefficient of the condensing flow in porous media inside pipes. The relations illustrated in both Figures are described by Eqn. (19).
Due to the positive values of the exponents, m and n in Eqn. (19) and to the negative value of the exponent l in the same equation, it is clear that as Br and /or We increase, Φ increases and as ε increases Φ decreases. It is clear that $\bar{h}_{cor}$ follows Φ in behaviour.

Conclusion
The main goal of this work was achieved. The work produced a simple equation for mean heat transfer coefficient of flow in porous media inside tubes with phase change. Eqn. (15) elucidates the relation obtained from this study. The resultant correlation was validated using CO_2 experimental results. A satisfactory degree of conformity was reached in the comparison study of the correlations obtained in this work with those from the experimental work and those stated in other literature works. Table 4 shows the resultant correlations.

Table 4. Correlations of this work.

Case	General correlation	
Evaporation	$\Phi = C\,(Br)^m (We)^n (\varepsilon)^l$	$\Phi = 3.3*10^{16} (Br_m)^{2.6} (We_m)^{-0.12} (\varepsilon)^{-0.43}$
Condensation	$\Phi = C\,(Br)^m (We)^n (\varepsilon)^l$	$\Phi = 1.577*10^{-4} (Br_m)^{0.435} (We_m)^{0.053} (\varepsilon)^{-4.84}$

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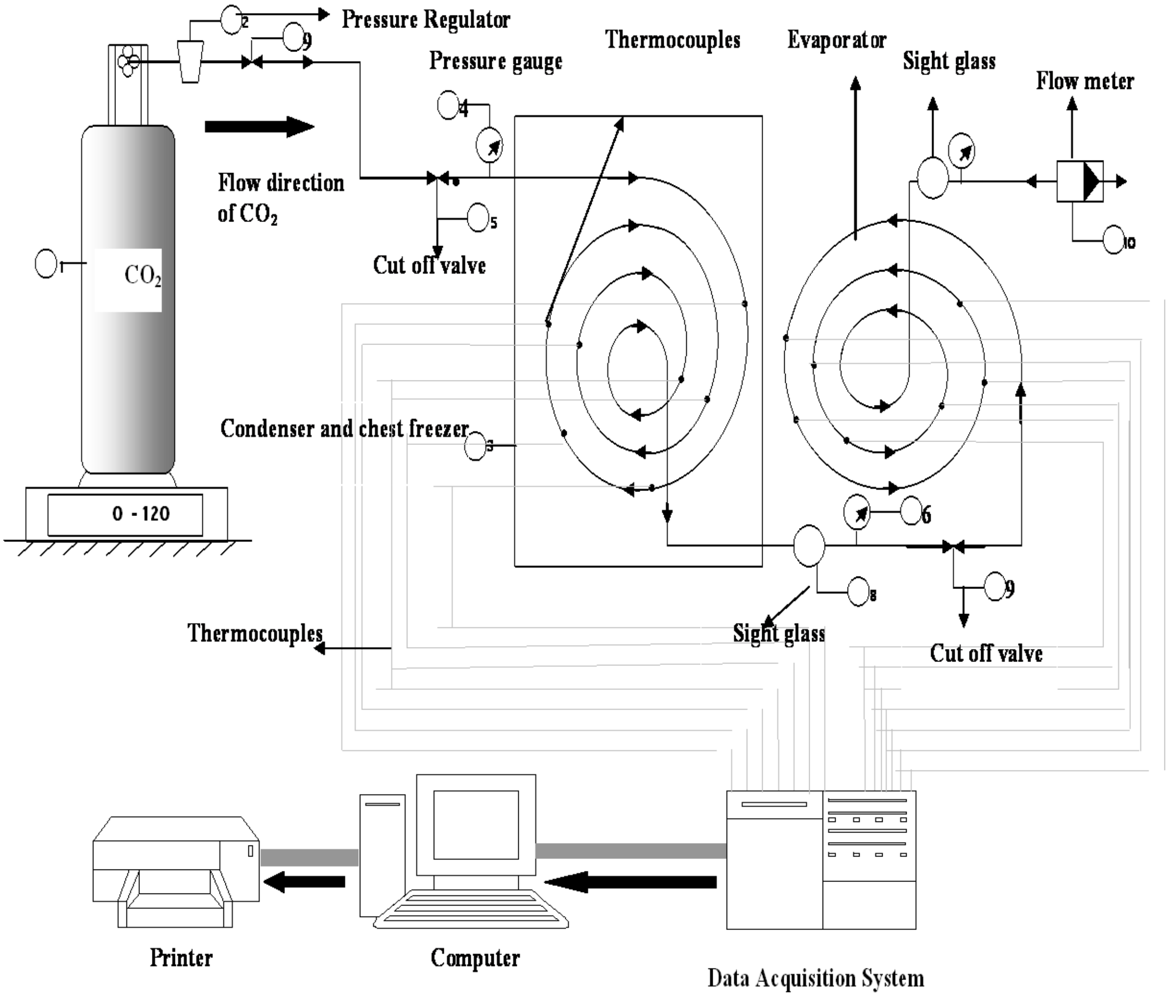

Fig. 1. Schematic diagram of the test apparatus.

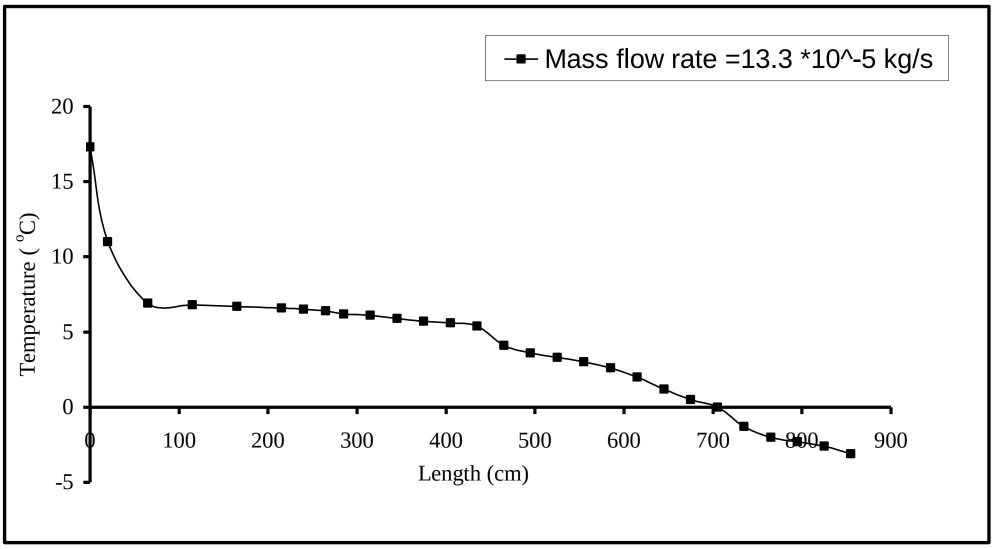

Fig. 2 Outside wall surface temperatures in (^{o}C) versus porous tube test section length for P_i= 4300 kPa, porosity =39.8% and mass flow rate = 13.3*10^{-5} kg/s during the condensation process.

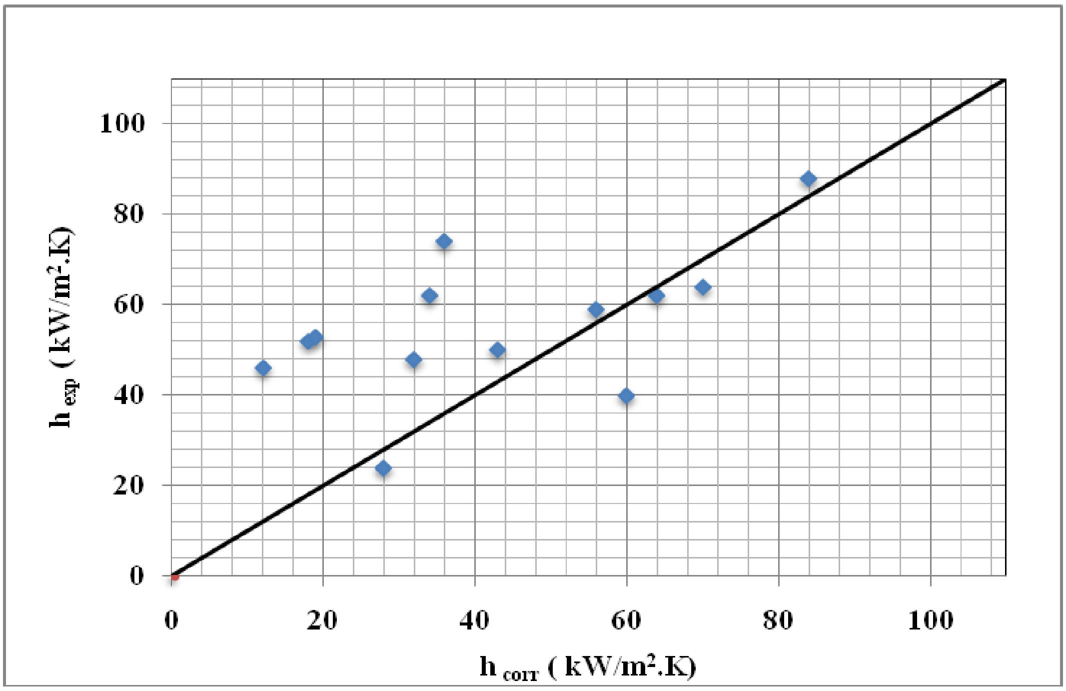

Fig. 3. Mean experimental heat transfer coefficient ($\bar{h}_{exp}$) vs. $\bar{h}_{corr}$ in evaporation conditions.

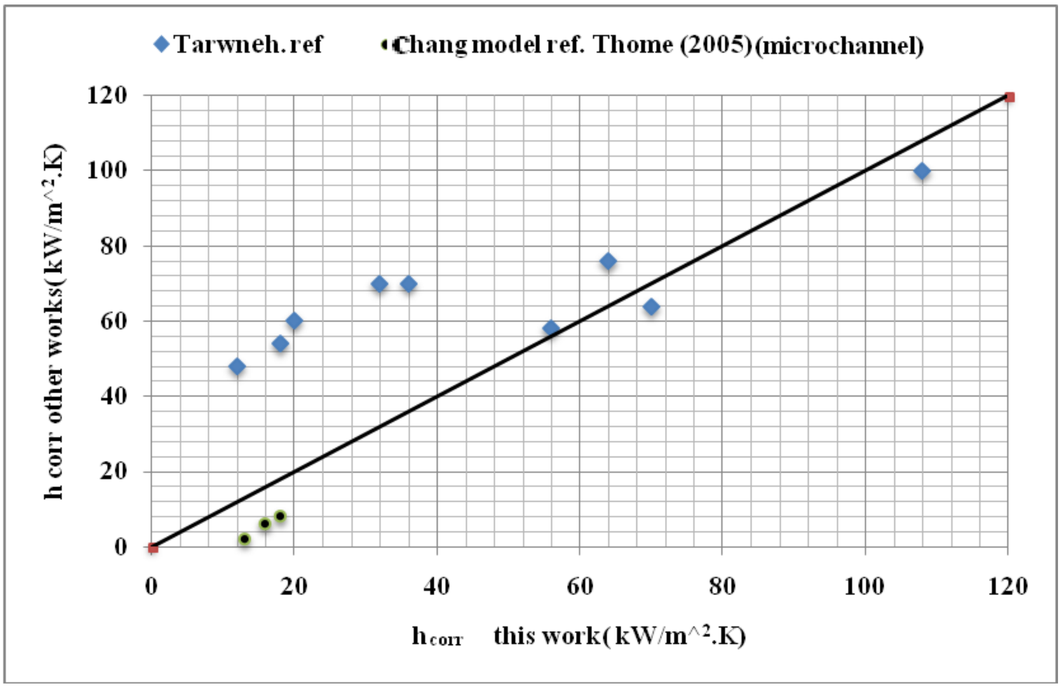

Fig. 4. Correlated heat transfer coefficient $\bar{h}_{corr}$ from other works (Al Tarawneh (2008) and Thome (2005)) vs. $\bar{h}_{corr}$ obtained in this work in evaporation conditions.

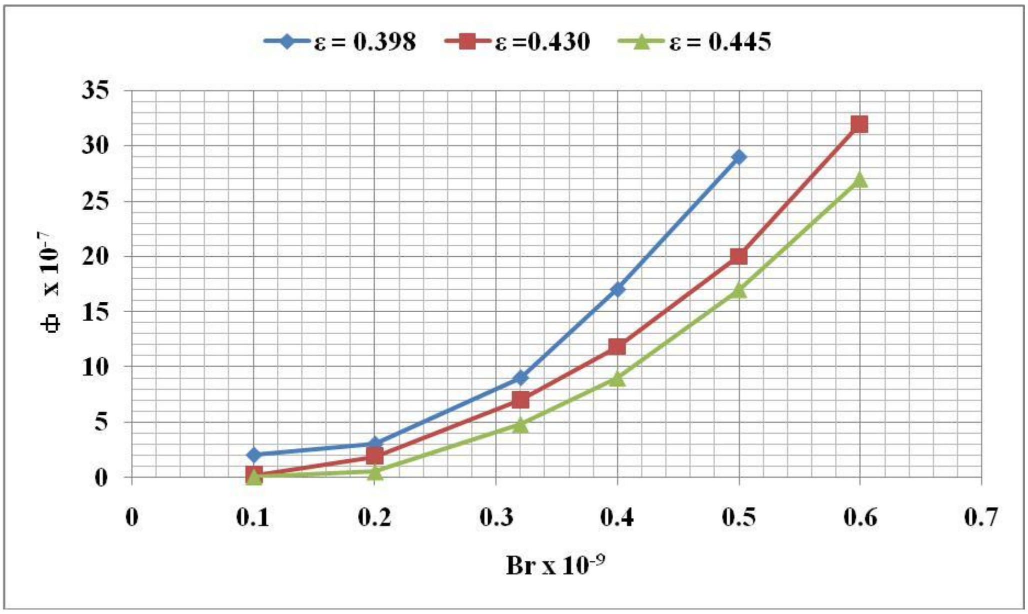

Fig. 5. **Φ** vs. Br at different values of (ε) for the evaporation process at (We = 2.5 x 10^{-3}).

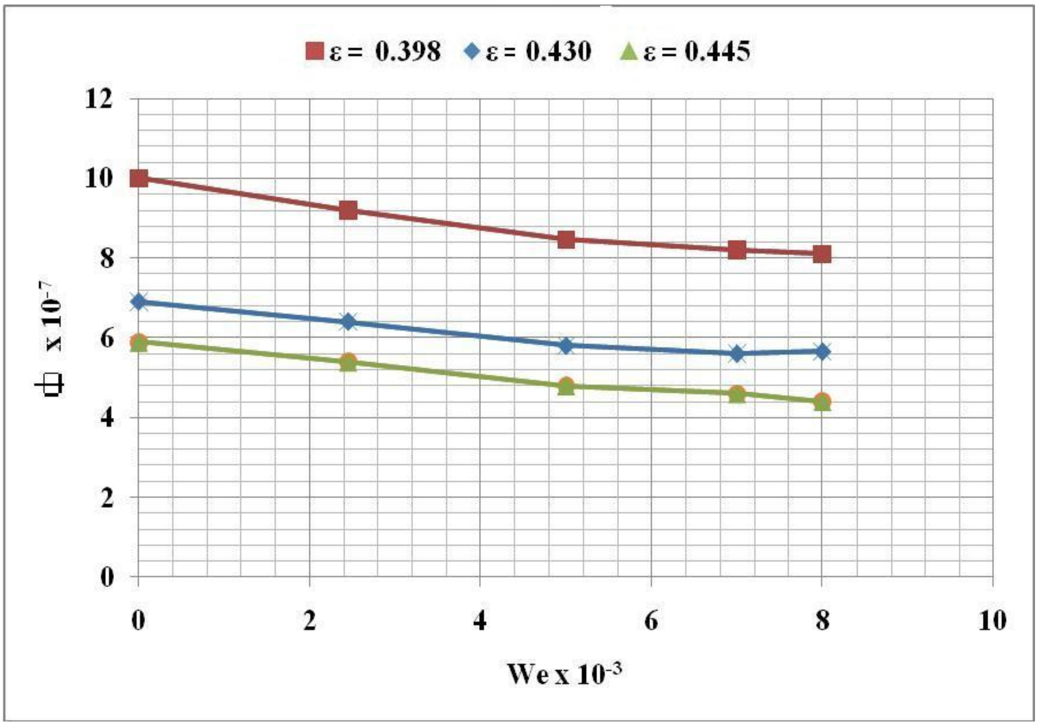

Fig. 6 Φ vs. We at different values of (ε) for the evaporation process at (Br = 0.3 x 10^{-9}).

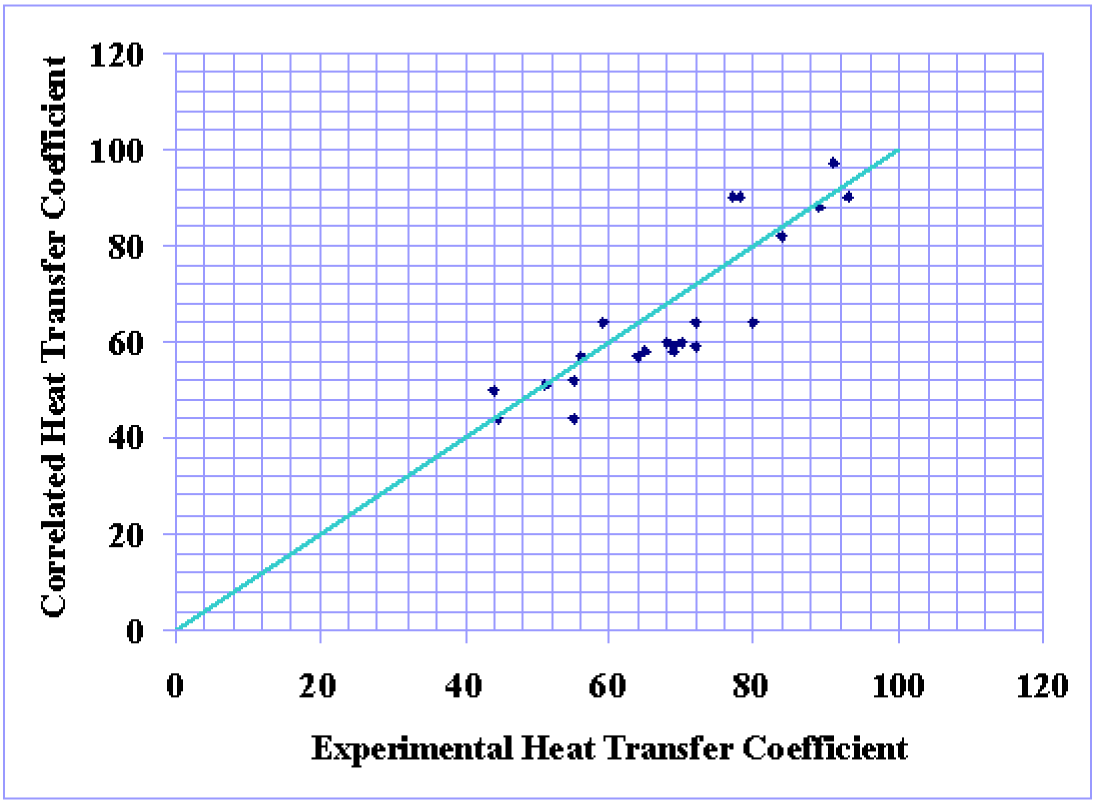

Fig. 7. Mean experimental heat transfer coefficient ($\bar{h}_{exp}$) vs. $\bar{h}_{corr}$ in condensation conditions.

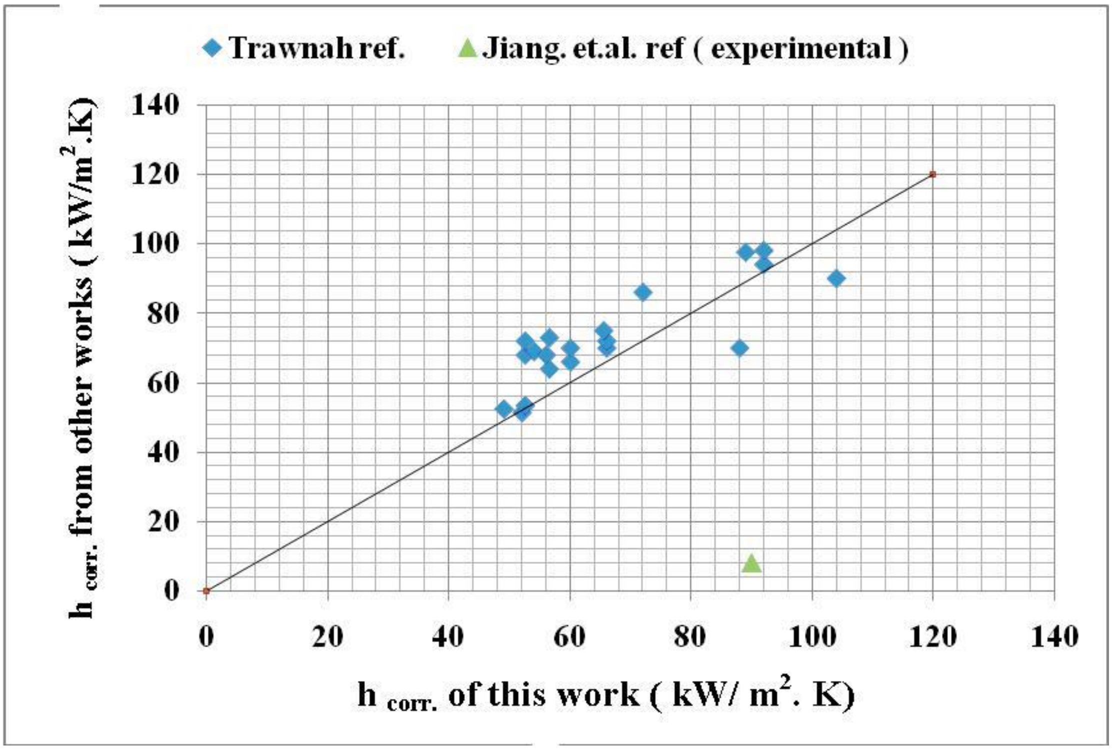

Fig. 8. Correlated heat transfer coefficient $\bar{h}_{corr}$ from other works (Al Tarawneh (2008) and Jiang et al. (2004)) vs. $\bar{h}_{corr}$ this work in condensation conditions.

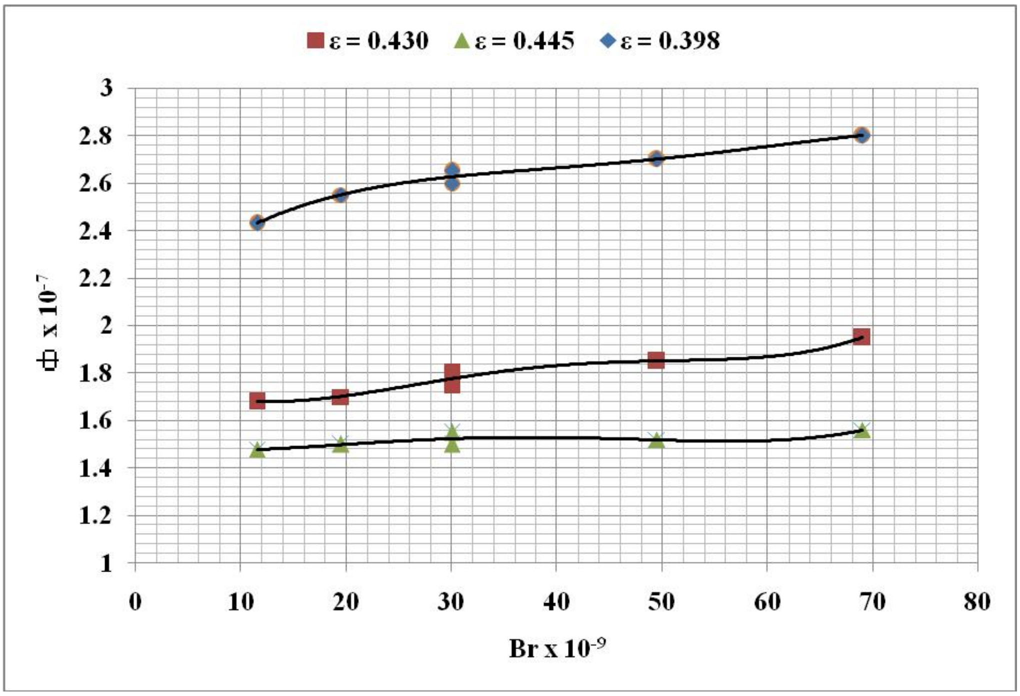

Fig. 9. **Φ** vs. Br at different values of (ε) for the condensation process at (We = 36.8×10^{-3}).

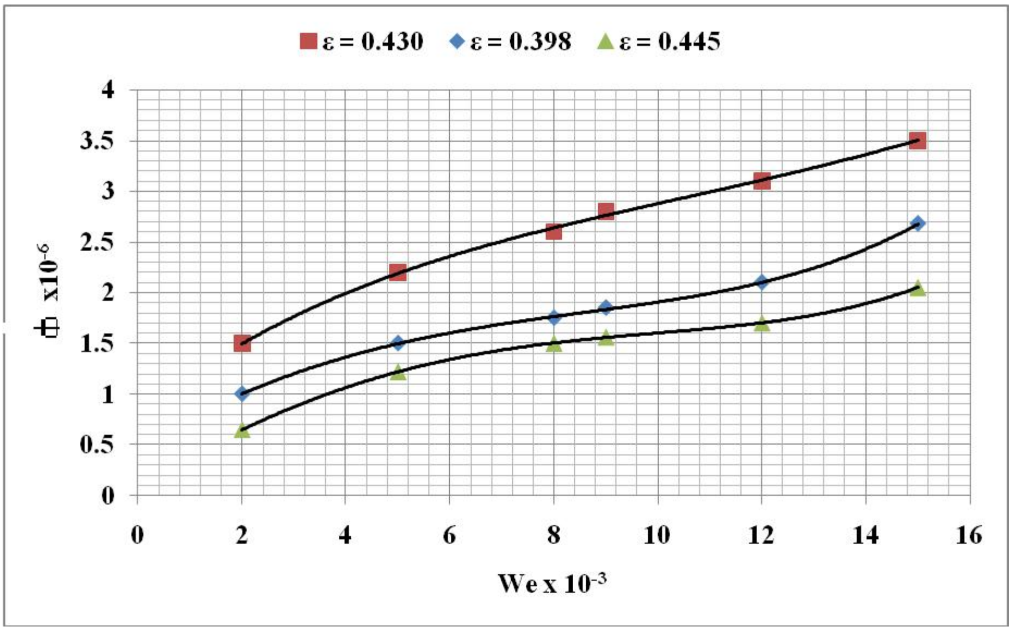

Fig. 10. **Φ** vs. We at different values of (ε) for the condensation process at (Br = 7.7 x 10^{-9}).