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COMPUTER CODE OF TWO-PHASE FLOW IN GEOTHERMAL WELLS PRODUCING WATER AND/OR WATER-CARBON DIOXIDE MIXTURES

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ABSTRACT

Mathematical well models are developed for pure water and for water-carbon dioxide mixtures. For the slug flow regime, three correlations (Orkiszewski's, Nicklin's and modified Nicklin's) are compared. An equation-of-state package for water-carbon dioxide mixtures is proposed as a function of pressure and temperature. The predicted values are compared with sixteen field cases, in which the maximum carbon dioxide content is 2.8 %.

INTRODUCTION

A wellbore configuration shown in Fig. 1 is used for a computer code of the two-phase flow in geothermal wells. Well inclination, diameter of conduit and heat loss to surrounding formations are included in the code. Two sets of computer codes, a GSW code and a GCW code, are developed. The GSW code is applicable to a pure water system. The GCW code is an extended version of the GSW code, and has a routine to calculate the phase behavior and properties of a water-carbon dioxide system. The GSW code is described here and the GCW code is described in the next section.

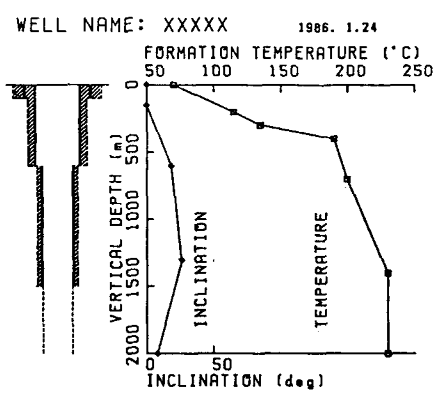

Fig. 1. Model of well configuration.

A flow diagram of the GSW code is shown in Fig. 2. Thermodynamic properties of water and steam are estimated by the formulas in JSME STEAM TABLES. The GSW code can calculate a flashing point and profiles of pressure, temperature, enthalpy, steam quality, density and flow regime. An example output of the GSW code is show in Fig. 3 for a hypothetical well.

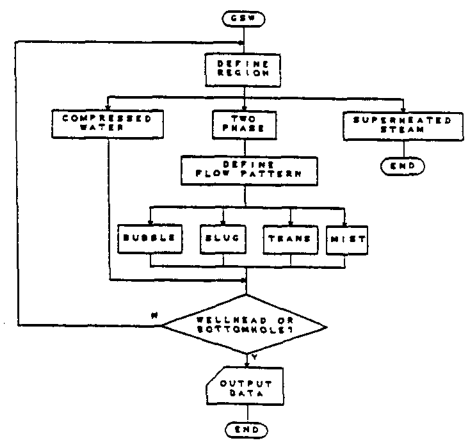

Fig. 2. Flow diagram of a GSW code

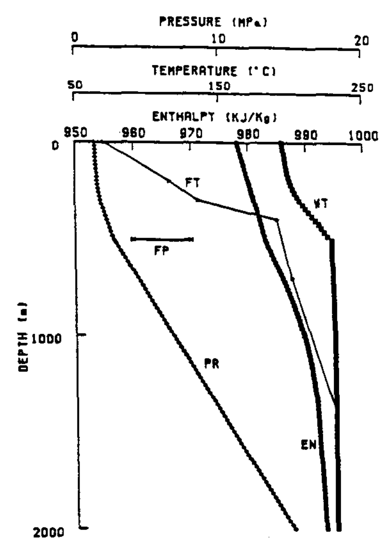

Fig. 3. An example output of the GSW code, PR:Pressure, WT:Temperature of wellbore, EN:Enthalpy, FP:Flashing point and FT:Formation temperature.

Griffith and Wallis correlation is used for bubble flow, and Duns and Ros correlations are used for transition and mist flows. For the slug flow regime, the following correlations are compared in this study:

(1) Orkiszewski correlation.

The mixture density and bubble rise velocity are evaluated by Orkiszewski correlation. A proposal by Gudmundsson et al. is employed to evaluate the liquid distribution factor Γ.

(2) Nicklin correlation.

The mixture density is evaluated by Griffith and Wallis correlation. The bubble rise velocity is calculated by a following equation obtained by Nicklin et al.:

$$V_b = \Lambda V_m + 0.35\sqrt{gd} \qquad (1)$$

where $\Lambda = 0.2$ when $N_{Re} > 8000$.

(3) Modified Nicklin correlation.

The Λ value of equation (1) is assumed to 0.1. The mixture density is evaluated by Griffith and Wallis correlation.

A comparison of these methods is shown in MODEL EVALUATION section.

MODEL FOR WATER-CARBON DIOXIDE MIXTURE

A flow diagram of the GCW code is shown in Fig. 4. An equation-of-state package for water-carbon dioxide mixture is constructed. The dew point pressure of the system is estimated by Dalton's law of partial pressures and Rault's law for solvent, but the mole fraction is replaced by the mass fraction according to Sutton:

$$P_d = P_w/(1-n_c) \qquad (2)$$

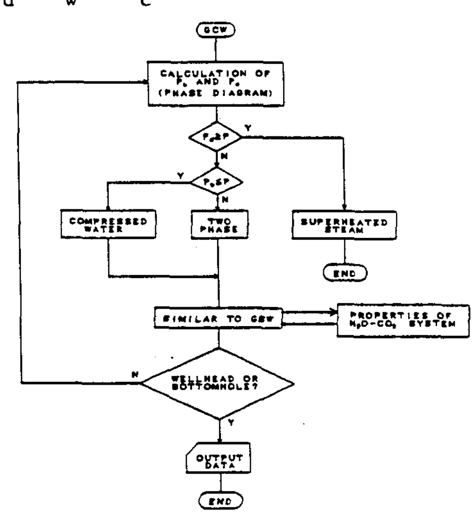

Fig. 4. Flow diagram of a GCW code.

The modified Henry's coefficient proposed by Sutton has been used so far to estimate the solubility of carbon dioxide in water, but this method considers only the effect of temperature. We propose a new approach to estimate the solubility of carbon dioxide in water as a function of temperature and pressure. Experimental solubility data of carbon dioxide in water are collected as shown in Fig. 5 from Dodds et al., Ellis et al. and Takenouchi et al. Polynominal fittings are employed in the several pressure levels from 0.1 MPa to 30 MPa. The intermediate value is interpolated.

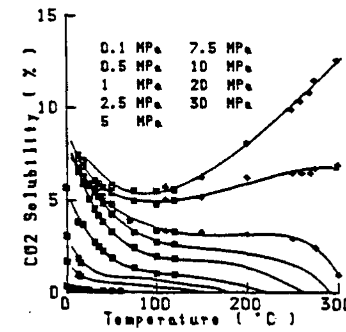

Fig. 5. Compiled solubility data of carbon dioxide in water.

The following matters are estimated from Fig. 5:

(1) Bubble point pressure.

When the concentration of carbon dioxide in the system is known, the bubble point is able to be calculated as a function of temperature. If a calculated pressure is greater than the bubble point, the system is in the compressed water region. If the pressure is less than the bubble point, the system is in the two-phase region. If the pressure is equal to the bubble point, this depth is a "Flashing point".

(2) Distribution of carbon dioxide in liquid phase.

In the two-phase region, mass fraction of carbon dioxide in liquid phase is equal to the solubility of carbon dioxide in water at the calculated temperature and pressure.

(3) Distribution of carbon dioxide in gas phase.

In the two-phase region, mass fraction of carbon dioxide in gas phase is calculated by the following modified Dalton's law according to Sutton:

$$n_{gc} = P_c/P \qquad (3)$$

$$P_c = P - P_w \qquad (4)$$

(4) Mass fraction of gas phase(quality).

In the two-phase region, mass fraction of gas phase is calculated by the following equation:

$$n_g = (n_c - n_{1c})/(n_{gc} - n_{1c}) \qquad (5)$$

A calculated phase diagram of the water-carbon dioxide system is shown in Fig. 6 about four concentrations of carbon dioxide in system from 0.5 % to 3 %. Dew point curves are not plotted since they are located so closely to the pure water curve. Bubble point curves are affected significantly by the concentration of carbon dioxide.

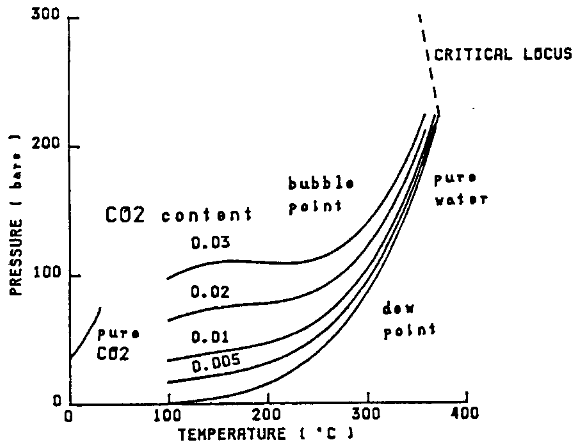

Fig. 6. Phase diagram of water-carbon dioxide system.

Thermodynamic properties of carbon dioxide are interpolated from the tables of Vargaftik. The properties of water-carbon dioxide system are calculated by the following equations for each region:

(1) Compressed water region.

The specific volume, viscosity and thermal conductivity of the solution are assumed to be the same as those of pure water. The specific enthalpy of the solution is calculated from

$$h(P,T,n_c) = (1-n_c)h_w(P,T) + n_c\{h_c(P,T) + h_{soln}(P,T)\} \quad (6)$$

The heat of solution is given by Ellis et al.

(2) Two-phase region.

The specific volume, viscosity and thermal conductivity of the liquid phase are assumed to be the same as those of pure water. The specific enthalpy of the liquid phase is calculated from

$$h_l(P,T,n_{lc}) = (1-n_{lc})h_w(P,T) + n_{lc}\{h_c(P,T) + h_{soln}(P,T)\} \quad (7)$$

The specific volume, specific enthalpy, viscisity and thermal conductivity of the gas phase are calculated from

$$v_g(P,T,n_{gc}) = (1-n_{gc})v_w(P_w,T) + n_{gc}v_c(P_c,T) \quad (8)$$

$$h_g(P,T,n_{gc}) = (1-n_{gc})h_w(P_w,T) + n_{gc}h_c(P_c,T) \quad (9)$$

$$\mu_g(P,T,n_{gc}) = (1-n_{gc})\mu_w(P_w,T) + n_{gc}\mu_c(P_c,T) \quad (10)$$

$$\lambda_g(P,T,n_{gc}) = (1-n_{gc})\lambda_w(P_w,T) + n_{gc}\lambda_c(P_c,T) \quad (11)$$

The properties of the system are weighted by mass fractions.

MODEL EVALUATION

Field data are summarized in Table 1. Case Nos. 1, 2 and 3 are for pure water and other thirteen cases for water-carbon dioxide mixtures. The maximum mass fraction of carbon dioxide is 2.8 %. The range of mass flow rate is from 10.8 t/h to 290.0 t/h.

(1) Pure water system, prediction by the GSW code.

Parameters at the wellhead of case No. 3 are summarized in Table 2 to evaluate bubble rise velocity formulas. Liquid Reynolds number is 19.0 million, and total superficial velocity is 8.22 m/s. The bubble rise velocities given by Orkiszewski, Nicklin and modified Nicklin correlations are 295.6 m/s, 2.26 m/s and 1.44 m/s respectively. The bubble rise velocity obtained by Orkiszewski correlation is an unreasonable big value, which shows that its correlation is not suitable for such a huge liquid Reynolds number. On the other hand, the bubble rise velocities given by Nicklin and modified Nicklin correlations seem to be reasonable.

Measured and calculated profiles of the case No.3 are shown in Fig. 7. In this case,

Table 1. Summary of field data.

Case No.	Well name	Mass fraction of CO_2 %	Wellhead Mass flow rate t/h total	liquid	gas	Wellhead pressure MPa	Bottom hole depth m	Bottom hole pressure MPa	Bottom hole temperature °C
1	W-1	0.0	67.9	47.0	20.9	1.54	945	6.25	246
2	W-1	0.0	114.5	79.0	35.5	1.51	945	5.25	250
3	W-2	0.0	131.0	97.7	33.5	2.96	998	5.21	264
4	C-2	1.0	158.0	148.0	10.0	2.11	1500	8.42	252
5	C-3	0.14	52.0	48.7	3.3	1.44	544	4.18	221
6	C-3	0.13	260.1	245.0	15.1	1.51	544	4.04	221
7	C-4	0.61	290.0	281.0	9.0	1.92	500	4.55	227
8	C-4	0.61	177.0	172.0	5.0	2.01	500	4.81	228
9	C-4	0.61	64.5	60.3	4.2	2.06	500	4.99	230
10	C-5	1.0	206.2	200.0	6.2	1.18	1300	9.25	210
11	C-5	1.0	117.4	114.0	3.4	1.38	1300	10.3	210
12	C-8	2.8	10.8	7.2	3.6	2.34	1500	12.4	265
13	C-8	2.8	15.6	10.4	5.2	2.78	1500	12.4	267
14	C-8	2.8	20.4	13.6	6.8	3.17	1500	12.4	266
15	C-10	1.0	172.0	163.0	9.0	2.89	1500	10.8	255
16	C-10	1.0	76.0	73.0	3.0	2.99	1500	11.8	254

Table 2. Summary of parameters at the wellhead of case No. 3.

Parameter	Unit		Value
Temperature,	°C	:	233
Pressure,	MPa	:	2.96
Quality,		:	0.256
Mass flow rate,	t/h	:	131.0
Well diameter,	m	:	0.3204
Surface tension,	N/m	:	0.0300
Specific volume of water,	m^3/kg	:	0.0012
Specific volume of steam,	m^3/kg	:	0.0676
Viscosity of water,	mPa·s	:	0.114
Viscosity of steam,	mPa·s	:	0.017
Superficial velocity of liquid phase,	m/s	:	0.41
Superficial velocity of gas phase,	m/s	:	7.81
Total superficial velocity,	m/s	:	8.22
Liquid Reynolds number,	$\times 10^6$	:	19.0
Bubble rise velocity by Orkiszewski,	m/s	:	295.6
Bubble rise velocity by Nicklin,	m/s	:	2.26
Bubble rise velocity by this work,	m/s	:	1.44

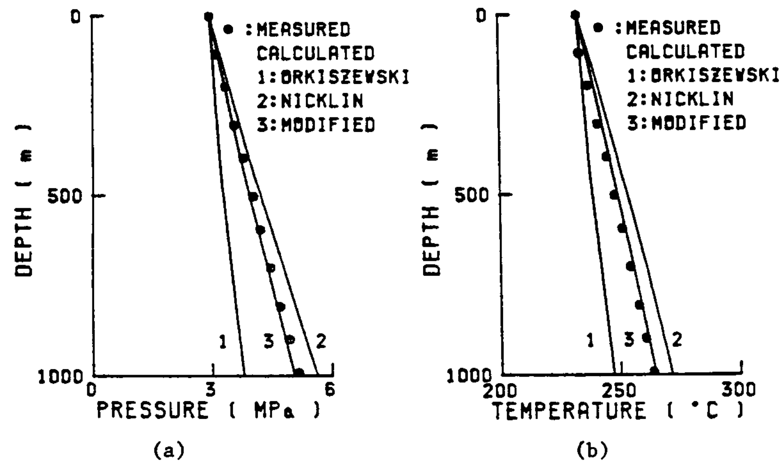

Fig. 7.
Measured and calculated profiles of the case No. 3.

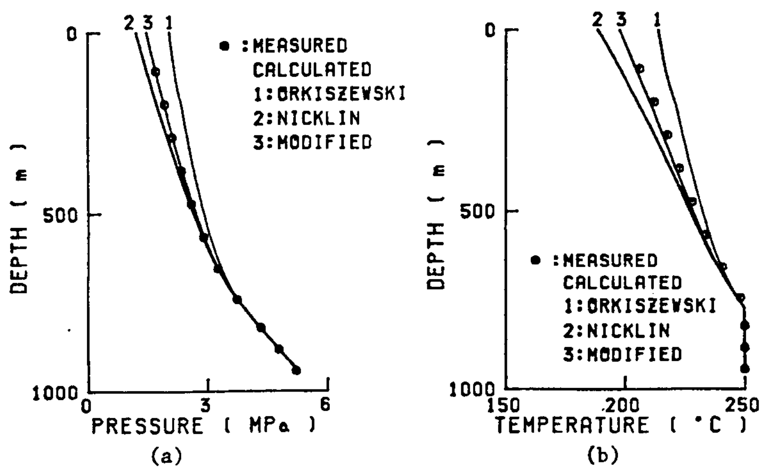

Fig. 8.
Measured and calculated profiles of the case No. 2.

calculation begins from the wellhead condition, because the two-phase state occurs at the bottom hole and the steam quality is not given there. The calculated profiles by the modified Nicklin correlation make an accurate prediction of the field data. The Orkiszewski correlation underestimates, and the Nicklin correlation overestimates in this case. Measured and calculated profiles of the case No. 2 are shown in Fig. 8. In this case, the calculation begins from the bottom hole. The calculated flashing point agrees very well with the observed position. The modified Nicklin correlation satisfactorily predicts the field data.

Calculated results at the wellhead by the modified Nicklin correlation are summarized in the upper part of Table 3.

(2) Water-carbon dioxide system, prediction by the GCW code.

Calculated profiles of 1 % carbon dioxide content and pure water (0 %) are compared with measured data in Fig. 9, in which the effect of carbon dioxide content is obvious. The calculated flashing point deepens from 594 m to 911 m with increasing carbon dioxide content to 1 %.

Distributions of carbon dioxide between both phases are calculated for the case No. 15 as shown in Fig. 10. The gas phase contains much more carbon dioxide than the liquid phase.

Table 3. Summary of calculated results by modified Nicklin.

Case No.	Mass fraction of CO_2	Wellhead					Flow* regime
		Quality	Mass fraction of CO_2 liquid	Mass fraction of CO_2 gas	pressure	temperature	
	%	%	%	%	MPa	°C	
1	0.0	11.0			1.48	198	C,B,S
2	0.0	12.1			1.49	198	C,B,S
3**	0.0	19.3***			5.07***	265***	S
4	1.0	10.0	0.06	9.47	2.20	212	C,B,S
5	0.14	7.4	0.01	1.81	1.21	181	C,B,S
6	0.13	6.1	0.01	2.00	1.43	195	C,B,S
7	0.61	4.4	0.08	11.9	2.18	210	C,B,S
8	0.61	4.3	0.08	12.4	2.25	212	C,B,S
9	0.61	4.7	0.08	11.4	2.18	211	C,B,S
10	1.0	5.7	0.08	16.3	1.40	187	C,B,S
11	1.0	4.8	0.10	19.0	1.56	190	C,B,S
12	2.8	8.1	0.44	29.7	4.11	232	C,B
13	2.8	7.8	0.49	30.2	4.57	237	C,B
14	2.8	8.7	0.42	27.7	4.20	234	C,B,S
15	1.0	8.2	0.11	10.9	2.79	224	C,B,S
16	1.0	8.0	0.11	11.2	2.76	223	C,B,S

* C = compressed water
B = bubble
S = slug
T = transition
M = mist

** Calculation begins from wellhead.

*** At bottom hole.

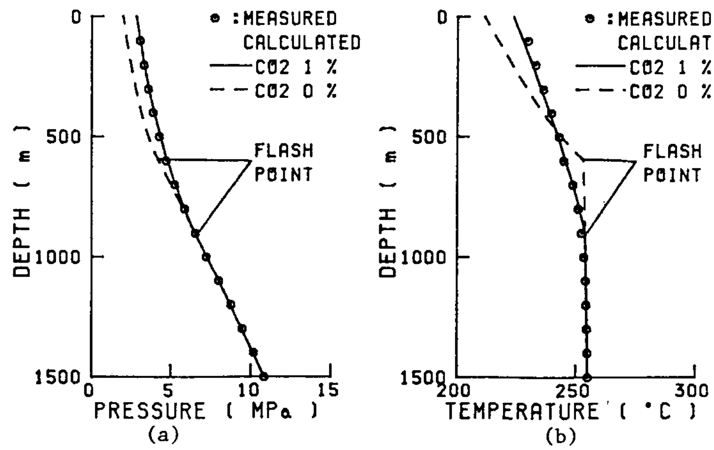

Fig. 9.
Measured and calculated profiles of the case No. 15.

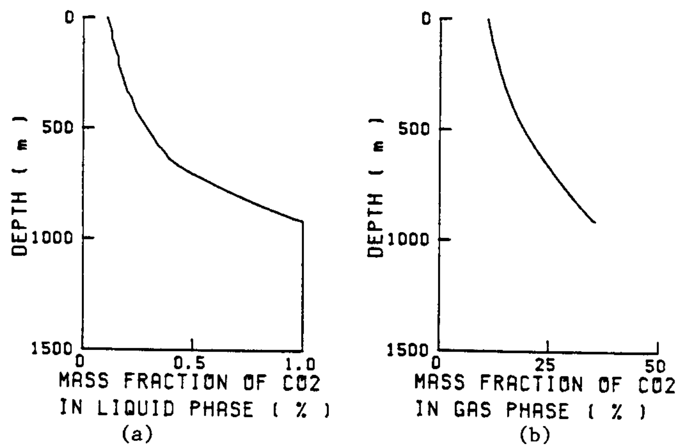

Fig. 10.
Distributions of carbon dioxide between liquid and gas phases for the case No. 15.

Calculated results at the wellhead by the modified Nicklin correlation are summarized in the lower part of Table 3.

(3) Comparison of calculated results with field data.

The predicted pressure losses are compared with measured data in Table 4. For the pure water system, the case No. 1, 2 and 3, the modified Nicklin correlation is better than the others in this study. For the water-carbon dioxide system, following comments are obtained. At low mass flow rate in the well C-8(case Nos. 12, 13 and 14), calculated data are primarily located in compressed water region and bubble flow regime, and the prediction of pressure losses does not agree with field data. For the other cases, the slug flow regime appears in a considerable length of the two-phase region. In ten cases from No. 4 to No. 16 except Nos. 12, 13 and 14, calculated pressure losses fall in ten-percent deviation range in most cases with the Nicklin and/or modified Nicklin correlations. Standard deviations for all cases are 15.57 %, 9.78 % and 7.26 % for Orkiszewski, Nicklin and modified Nicklin correlations, respectively.

One of sources introducing errors is supposed to be the measuring method of carbon dioxide content. The content is usually calculated from the analysis of carbon dioxide in the wellhead steam.

Table 4. Comparison of calculated pressure losses with field data.

Case No.	Pressure loss between bottom hole and wellhead MPa				Percentage error* between calculated and measured ΔP		
	measured	calculated					
		Orkiszewski	Nicklin	modified	Orkiszewski	Nicklin	modified
1	4.71	4.63	4.91	4.76	−1.69	4.24	1.06
2	3.74	3.20	4.04	3.78	−14.44	8.02	1.07
3**	2.25	0.85	2.69	2.12	−62.22	19.56	−5.78
4	6.31	5.44	6.52	6.22	−13.79	3.33	−1.43
5	2.74	3.05	3.02	2.96	11.31	10.22	8.03
6	2.53	2.31	2.74	2.61	−8.70	8.30	3.16
7	2.63	2.10	2.49	2.38	−20.15	−5.32	−9.51
8	2.80	2.24	2.64	2.55	−20.00	−5.71	−8.93
9	2.93	2.88	2.86	2.81	−1.71	−2.39	−4.10
10	8.07	7.37	8.02	7.85	−8.67	−0.62	−2.72
11	8.92	8.60	8.82	8.73	−3.59	−1.12	−2.13
12	10.06	8.26	8.26	8.26	−17.89	−17.89	−17.89
13	9.62	7.84	7.84	7.84	−18.50	−18.50	−18.50
14	9.23	8.46	8.21	8.19	−8.34	−11.05	−11.27
15	7.91	7.44	8.23	8.04	−5.94	4.04	1.64
16	8.81	9.13	9.11	9.00	3.63	3.41	2.16
Average deviation,				%	−11.92	−0.01	−4.07
Average absolute deviation,				%	13.79	7.73	6.21
Standard deviation,				%	15.57	9.78	7.26

* Percentage error = $\frac{100(P_{calc} - P_{meas})}{P_{meas}}$

** Calculation begins from wellhead.

CONCLUSIONS

1. Mathematical well models are developed for pure water and for water-carbon dioxide mixtures.
2. For the slug flow regime, three correlations for bubble rise velocity are compared. The Orkiszewski correlation estimates the velocity too large. The Nicklin correlation or modified one estimates the reasonable velocity.
3. An equation-of-state package for water-carbon dioxide mixtures is proposed as a function of pressure and temperature.
4. The predicted values are compared with sixteen field cases, in which maximum carbon dioxide content is 2.8 %. Standard deviations are 15.57 %, 9.78 % and 7.26 % for Orkiszewski, Nicklin and modified Nicklin correlations, respectively.
5. Following problems seem to remain still in this study:

(1) Determination between bubble and slug flow regimes at a low mass flow rate in a large diameter wellbore.
(2) Assumption of a constant slip velocity of 0.24 m/s at the bubble flow regime.
(3) Limiting number of experiments available to estimate solubility of carbon dioxide in water.

NOMENCLATURE

- d = diameter
- g = acceleration of gravity
- h = specific enthalpy
- n = mass fraction
- N_{Re} = Reynolds number
- P = pressure
- T = temperature
- v = specific volume
- V_b = bubble rise velocity
- V_m = total superficial velocity
- λ = thermal conductivity
- μ = viscosity

subscripts

- c = carbon dioxide
- d = dew point
- g = gas phase
- l = liquid phase
- w = water

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