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A LOCAL VOID AND SLIP MODEL USED IN BODYFIT-2PE

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ABSTRACT

A local void and slip model has been proposed for a two-phase flow without the need of fitting any empirical parameters. This model is based on the assumption that all bubbles have reached their terminal rise velocities in the two-phase region. This simple model seems to provide reasonable calculational results when compared with the experimental data and other void and slip models. It provides a means to account for the void and slip of a two-phase flow on a local basis. This is particularly suitable for a fine mesh thermal-hydraulic computer program such as BODYFIT-2PE.

1.0 INTRODUCTION

In most of the computer codes[1-3] for subchannel, two-phase flow problems, empirical correlations are often used to calculate the subchannel void fractions and slip ratios. These correlations are used to account for the phase slip and the non-homogeneities in two-phase flows. Some of the commonly used ones are the Levy correlation[4], the Lellouche and Zolotar correlation[5], the Zuber-Findlay drift-flux model [6], and the Smith correlation.[7] All these correlations are applied on a global basis on the subchannel of the rod bundle. Therefore, the detailed distribution of the void within the bundle is lost.

2.0 OTHER GLOBAL MODELS

The Levy correlation and the Lellouche and Zolotar correlation are similar in their approaches. They calculate the void fraction by first determining the bubble detachment point and then determining the relationship between the true flow quality and the thermal-equilibrium quality. In the Levy correlation, the relationship among the actual quality x, the equilibrium quality x_e, and the detachment quality x_d is given as

$$x = x_e - x_d \exp\left(\frac{x_e}{x_d} - 1\right). \tag{1}$$

This form satisfies the curves of x versus x_e derived from experiment. The detachment quality x_d is then expressed in terms of the specific heat of saturated liquid, c_p, the latent heat of vaporization, h_{fg}, and the bulk subcooling of the fluid at the bubble departure point, ΔT_d, as

$$x_d = -\frac{c_p\ \Delta T_d}{h_{fg}}. \tag{2}$$

The bulk subcooling is then expressed as a complicated function of the Prandtl number, the surface heat flux, the shear at the wall, the surface tension, and the buoyancy force on the bubble. The actual quality is then substituted into the homogeneous equation for void fraction,

$$\alpha = \frac{x}{x + \frac{\rho_g}{\rho_f}(1-x)}. \tag{3}$$

In the Lellouche and Zolotar model, a profit fit of the void fraction curve from single-phase to fully-developed forced convection gives

$$x = \frac{x_e - x_d\left[1-\tanh\left(1 - \frac{x_e}{x_d}\right)\right]}{1 - x_d\left[1-\tanh\left(1 - \frac{x_e}{x_d}\right)\right]} \tag{4}$$

instead of Eq. (1). The detachment quality x_d is similar to Eq. (2) as

$$x_d = -\frac{c_p Z}{h_{fg}}, \tag{5}$$

where Z is expressed in terms of heat flux, heat transfer coefficients, and pressure at the detachment point. Once x is known from Eq. (4), void fraction α is found from

$$\alpha = \frac{x}{C_o\left[x + \frac{\rho_g}{\rho_f}(1-x)\right] + \frac{\rho_g V_{gj}}{G}} \tag{6}$$

where C_o is the distribution factor, V_{gj} is the drift flux velocity, and G is the mass flux. Note that if $C_o = 1$ and $V_{gj} = 0$, Eq. (6) reduces to Eq. (3) for the homogeneous equilibrium model. The C_o is an empirical constant and is determined on a global basis across the channel. In order to avoid this empiricism in the above models, the following simple model has been proposed by EPRI.

3.0 THE PRESENT LOCAL MODEL

In this model, one assumes the bubbles have reached their terminal rise velocities locally as

$$V_g - V_\ell = 1.41\left[\frac{\sigma g\ (\rho_\ell - \rho_g)}{\rho_\ell^{\ 2}}\right]^{1/4}, \tag{7}$$

where V_g and V_ℓ are the axial velocities of the vapor and the liquid respectively. The lateral slip between the two phases are assumed to be zero.

The exact relationship between the quality and the void fraction is given by

$$\alpha = \frac{x}{x + \frac{\rho_g}{\rho_\ell}(1 - x)S}, \quad (8)$$

where S is the slip ratio of V_g/V_ℓ .

To express S in terms of $V_g - V_\ell$, the denominator can be rearranged to yield

$$x + \frac{\rho_g}{\rho_\ell}(1 - x)\left(1 + \frac{V_g}{V_\ell} - 1\right)$$

$$= x + \frac{\rho_g}{\rho_\ell}(1 - x) + \frac{\rho_g(1 - x)}{\rho_\ell V_\ell}\left(V_g - V_\ell\right)$$

$$= x + \frac{\rho_f}{\rho_\ell}(1 - x) + \frac{\rho_g(1 - \alpha)}{G}\left(V_g - V_\ell\right) .$$

Therefore, α can be written to give

$$\alpha = x\Big/\left[x + \frac{\rho_g}{\rho_\ell}(1 - x) + \frac{\rho_g(1 - \alpha)}{G}\left(V_g - V_\ell\right)\right] \quad (9)$$

This equation can be solved for α as

$$\alpha = \frac{B' - \sqrt{B'^2 - 4A'x}}{2A} \quad (10)$$

where

$$A' = \frac{\rho_g}{G}\left(V_g - V_\ell\right),$$

$$B' = x + \frac{\rho_g}{\rho_\ell}(1-x) + \frac{\rho_g}{G}\left(V_g - V_\ell\right),$$

and $V_g - V_\ell$ is given by Eq. (7). In order to insure that $\alpha = 0$ when $x = 0$, the + solution should be discarded in solving the quadratic equation. Also, when $x = 1$, $\alpha = 1$. Once α is known, S can easily be obtained through Eq. (8).

The advantage of this model is that it is simple and yet it provides direct information for the local void fraction and slip ratio without involving fitting of parameters. This model is programmed in the BODYFIT-2PE[8] code. BODYFIT-2PE is a steady-state/transient, three-dimensional computer program for thermal-hydraulic analyses of two-phase flow problems in light-water-reactor fuel assemblies. It uses the technique of the boundary-fitted coordinate system where all the physical boundaries are transformed to be coincident with constant coordinate lines in the transformed space. Therefore, the boundary conditions can be accurately represented without interpolation. The code uses the parabolic approximation for saving computer running time and storage. The physical models and the numerics are described in Ref. 8.

4.0 COMPARISON WITH OTHER MODELS AND EXPERIMENTAL DATA

This local void and slip model is used to calculate the hot and cold channel mass fluxes, qualities, and void fractions for a 4x4 rod bundle. Results of the calculation were compared with the test data measured by Columbia[9] for the 4x4 rod bundle. In the experiment, isokinetic sampling measurements of mass flow rate and enthalpy were carried out on the rod bundle array typical of a Boiling Water Reactor geometry. The physical dimension of the rod bundle as well as the computational meshes used in the BODYFIT calculation are given in Fig. 1. The mass flow rate and enthalpy of two selected subchannels, a hot and a cold channel at centrally symmetrical locations were measured by isokinetically extracting the entire flows and sending them through two calorimetry loops. These hot and cold subchannels are also outlined and marked H and C, respectively, in Fig. 1. The rod bundles were electron beam welded to the grid plate. The rod to rod spacing was maintained by placing specially machined grids at various axial locations. The grids were designed to have enough strength while producing minimum mixing. They are modeled in the BODYFIT calculation by head loss terms for different subchannels.

The 16 rods were electrically heated with a power distribution of two to one; two on the left half and one on the right half. After the steady state condition was attained, heat loss calibrations were performed. Enthalpy and flow data were taken at selected powers and flow rates for a series of inlet temperatures while the pressure was held constant at 1000 psia.

Six sets of experimental data with diversified test conditions were chosen to compare with the BODYFIT calculations. The test conditions were given in Table 1 along with the comparison between the experimental measurements (A) and BODYFIT-2PE calculations for various void and slip models - Homogeneous Equilibrium Model (B), Lellouche and Zolotar model (C), and the present local model (D). Figure 2(a) and 2(b) show the cold and the hot channel mass flow rates at the exit of the rod bundle. Figure 3(a) and 3(b) show the cold and the hot channel quality at exit. Comparisons were made between the experimental measurements and homogeneous equilibrium model (HEM) - model 1, the Lellouche and Zolotar model - model 2, and the present local model -model 3. In general, all three models agree well with the experimental measurements. The calculations based on the present local model were very close to those based on the HEM. This result seems expected from the fact that the relative phase velocity, $V_g - V_\ell$, is small compared to the flow rate G in the cases we have studied. This is evident in examining Eq. 9. Further comparison with cases where G is small will be a crucial test of the model. It should also be noted from Fig. 2 that there are significant amounts of cross flow going from the hot channels to the cold channels.

5.0 CONCLUSION

In summary, a simple void and slip model has been proposed for two-phase flow without the need for fitting any empirical parameters. This model is based on the assumption that all bubbles have reached their terminal rise velocities in the two-phase region. This assumption seems reasonable when the calculational results are compared with the experimental data and other void and slip models.

This does not mean the current model is perfect. It is a first attempt to use a void and slip model on a local basis suitable for a fine mesh computer program like BODYFIT. Further testing and improvement on the model is currently under way to study the effect of different flow regimes on the terminal rise velocities and low flow rates on the validity of the model.

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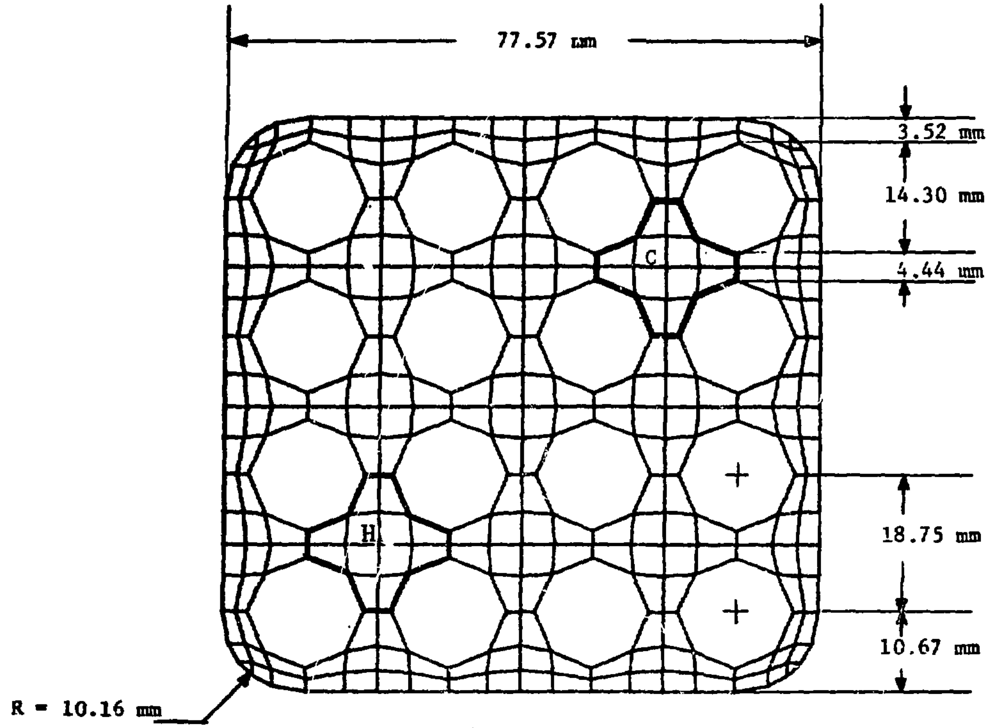
Table 1 Comparison between the experimental measurements and BODYFIT-2PE Calculations

	BUNDLE AVERAGE					COLD CHANNEL				HOT CHANNEL		
Run No.	G	H_{in}	H_{out}	X_{out}	HFLUX		G	H	X	G	H	X
219	1949	1.088	1.299	2.4	0.524	(A)	2274	1.258	- 0.3	1278	1.415	10.1
						(B)	2658	1.244	- 0.4	1590	1.399	9.7
						(C)	2535	1.238	- 0.7	1683	1.396	9.5
						(D)	2647	1.244	- 0.4	1596	1.398	9.6
224	1345	0.875	1.189	-4.8	0.539	(A)	1457	1.114	- 9.8	990	1.310	3.2
						(B)	1619	1.102	- 9.9	1253	1.297	2.8
						(C)	1603	1.098	-10.1	1314	1.300	3.0
						(D)	1612	1.101	- 9.9	1265	1.297	2.8
225	1345	0.875	1.236	-1.7	0.621	(A)	1581	1.158	- 6.9	902	1.392	8.6
						(B)	1789	1.145	- 7.0	1092	1.384	8.5
						(C)	1726	1.136	- 7.6	1181	1.381	8.3
						(D)	1780	1.145	- 7.1	1100	1.383	8.4
232	2717	1.072	1.276	0.9	0.708	(A)	3594	1.226	- 2.4	1785	1.390	8.4
						(B)	3523	1.227	- 1.1	2197	1.366	7.8
						(C)	3390	1.221	- 1.6	2305	1.365	7.8
						(D)	3513	1.227	- 1.1	2205	1.365	7.8
242	2021	1.201	1.384	8.0	0.470	(A)	2269	1.354	6.1	1538	1.493	15.3
						(B)	2561	1.321	4.9	1739	1.487	15.6
						(C)	2457	1.322	4.9	1825	1.481	15.2
						(D)	2559	1.322	4.9	1739	1.486	15.5
245	2033	0.755	1.157	-6.9	1.045	(A)	2497	1.065	-13.0	1373	1.340	5.1
						(B)	2440	1.048	-13.1	1760	1.303	3.4
						(C)	2441	1.041	-13.5	1847	1.310	3.9
						(D)	2433	1.048	-13.1	1774	1.303	3.4

NOMENCLATURE: G - Mass Flux (Kg/m^2/sec.), H - Enthalpy (MJ/Kg), HFLUX - heat flux (MJ/m^2/sec), X - Percent (%)
(A) - Experimental Measurements, (B) - HEM Model, (C) - Lellouche & Zolotar Model, (D) - Local Model



Hydraulic Diameter = 13.28 mm

Flow Area = $3.36 \times 10^{-3}\ m^2$

Heated Length = 3.658 m

Power Ratio = 2 to 1

Fig. 1 Mesh Structure and geometrical dimensions for the Columbia University 4x4 rod bundle

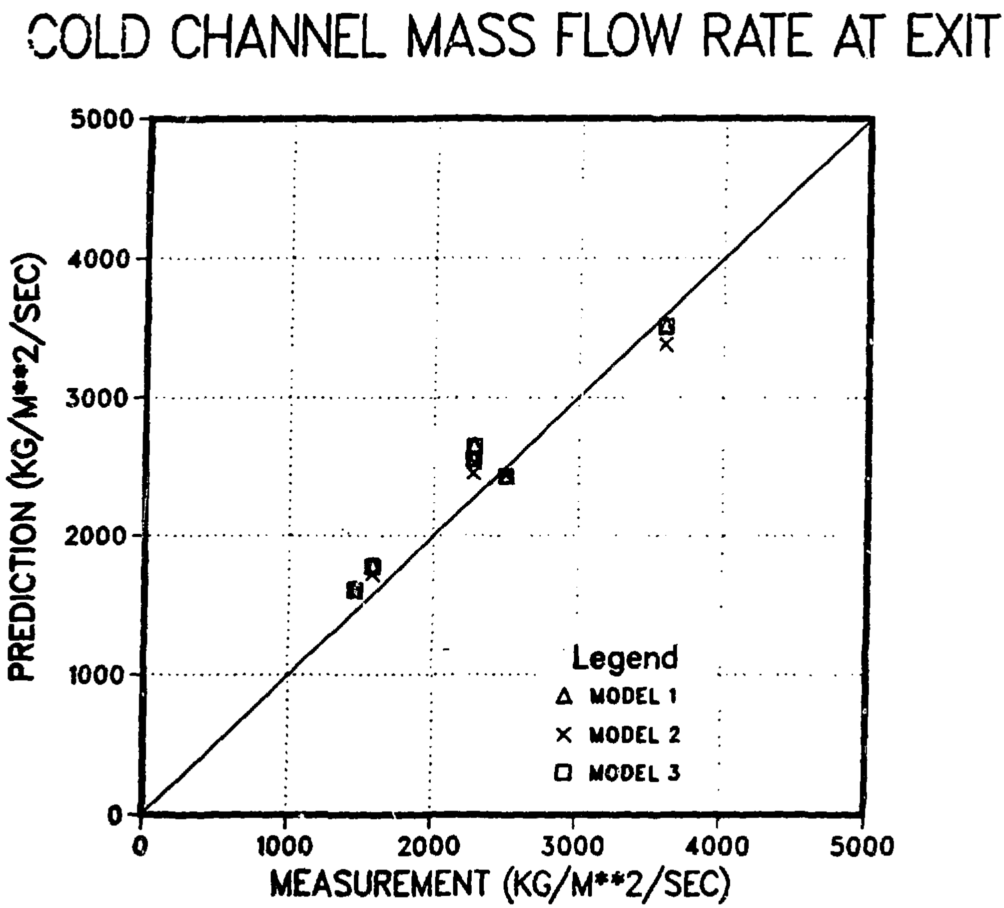


Fig. 2(a) Comparison of cold channel mass flow rate at exit between the experimental measurements and the BODYFIT-2PE calculations for various void and slip models.

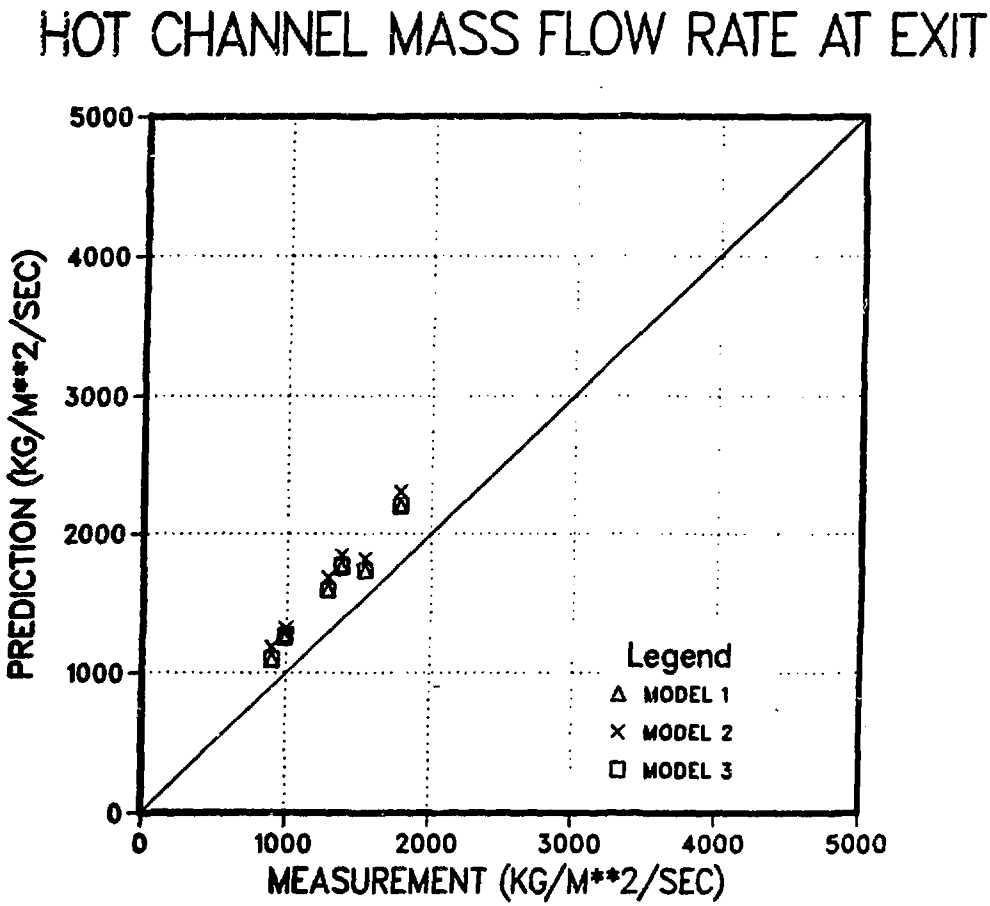


Fig. 2(b) Comparison of hot channel mass flow rate at exit between the experimental measurements and the BODYFIT-2PE calculations for various void and slip models.

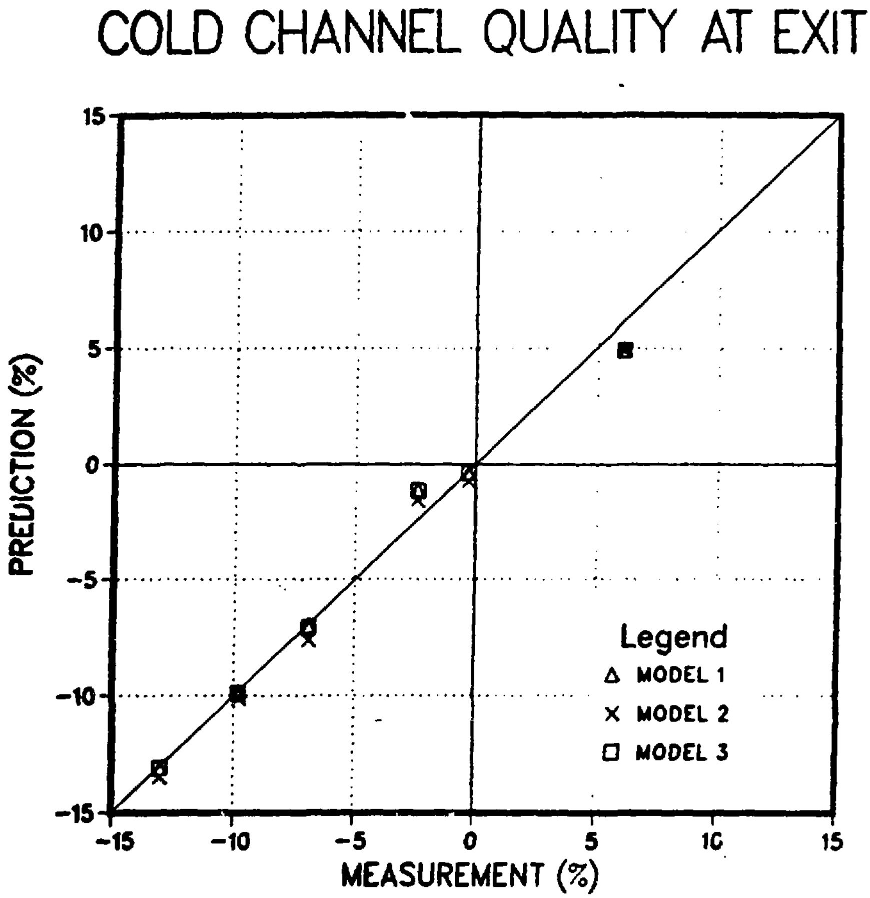


Fig. 3(a) Comparison of cold channel quality at exit between the experimental measurements and the BODYFIT-2PE calculations for various void and slip models.

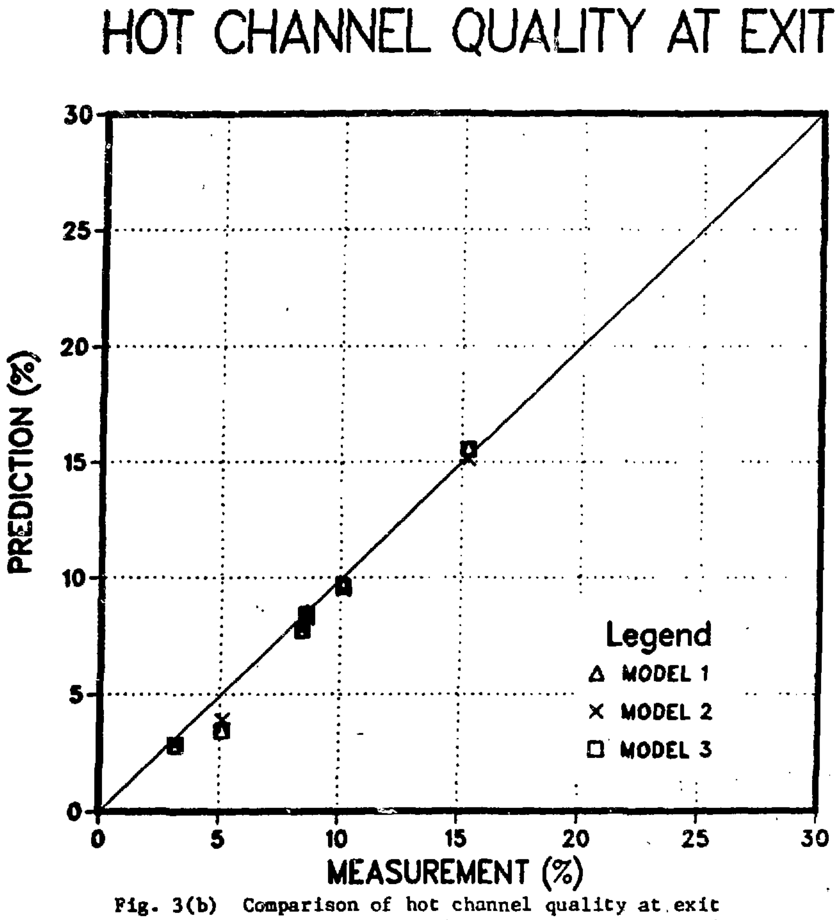


Fig. 3(b) Comparison of hot channel quality at exit between the experimental measurements and the BODYFIT-2PE calculations for various void and slip models.