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PREDICTING TWO-PHASE FLOW DISCHARGE THROUGH LATERAL BRANCHES CONNECTED TO A HORIZONTAL MAIN PIPE

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ABSTRACT

The present paper is a sequel of some other together whom it is to be viewed as a work in progress on the subject of phases subdivision through branching conduits, characterized by stratified two-phase flow in a large horizontal main pipe and reduced diameter upward, downward, or lateral branches, attached to the pipe wall. In particular, the study of the involved physical phenomena resulted in the proposal of semi theoretical expressions for the branch exit quality and, then, of the discharged mass flow. In previous MFIP Conference editions, the complete treatment of the first two branches typologies has been presented and the study included very positive comparisons against most quoted experimental data of literature. Here, after a brief outline of the model relevant the third branch typology, it also will be tested about its prediction capability. Again, one sees that the model performs quite well.

1. INTRODUCTION

The prediction of the two-phase mass flow discharge through a branch or a small break attached in a large horizontal main pipe is one of the most important issues in safety studies relevant accidental transients in high energy two-phase flow systems. For instance, it is very important in the Light Water nuclear Reactors (LWRs) during a small break Loss of Coolant Accident (LOCA), in pipelines network equipments for dangerous fluid transfer, in natural gas phase separator and off-shore oil well lines, in chemical batch or continuous reactors, and so on.

To introduce the matter, consider a branching conduit consisting of a horizontal main pipe, with inlet section and outlet one (run section) of equal large diameter, and a vertical upward, or downward, or horizontal lateral branch, generally characterized by a quite smaller diameter with respect to the main pipe. Following Zuber (1981), in large horizontal pipes, manifolds or vessels interested by two-phase flow, if the flow rates of the phases are low enough so that the gravitational forces overcome the frictional ones, there is a natural tendency to flow stratification. This considerably influences the mass flow discharge through branches connected to these volumes, because the exit mass flow quality strongly depends on the liquid level in the main pipe.

In fact, in case of branch located at the top of the pipe, for a sufficiently large distance between the branch entrance and the gas-liquid interface, only gas enters the branch. However, for smaller distances, the interface below the branch is locally raised due to Bernoulli effect pressure drop. In these conditions, a no negligible amount of liquid, in form of various dimension drops, can be torn away from the interface and enter the branch. On the contrary, in case of branch located at the bottom, the mass outflow is mainly liquid, however it may contain gas component due to vortex suction or vortex-free pull-through.

Finally, in case of a branch located at the side, liquid entrainment or gas pull-through will might occur, depending on the elevation of the liquid level relative to the branch location.

In the past years, in order to study the above depicted scenario, many Authors were involved in a significant experimental research effort, using air-water and steam-water flows and branches of various orientations and diameters, attached to horizontal main pipes. Different pressure operating conditions have been also employed (Reimann and Smoglie, 1983; Reimann and Khan, 1984; Maciaszek and Menponteil, 1986; Smoglie et al., 1987; Reimann et al., 1988). The most significant research works showed that pronounced variations of the phase separation can occur in the branch with respect to that in the main pipe, and that the amount of two-phase discharge depends on the flow regime in the main pipe region near to the branch, as well on conduit geometry, and fluid properties.

In addition, several expressions for the prediction of branch exit quality, usually called x_3, were derived mainly from dimensional analysis, empirical fitting to experimental data (Smoglie et al., 1987), as well as from phenomenological or theoretical models (e.g., Azzopardi and Whalley, 1982; Yonomoto and Tasaka, 1988, 1991).

In most of the proposed expressions for x_3, the key parameter is assumed to be the ratio $r = h/h_b$, between the distance, h, of the branch entrance and the gas-liquid interface and the value, h_b, of such a distance at the beginning of the entrainment (critical distance).

Castiglia and Giardina (2002) introduced a new semi-theoretical solution to the problem, which could be classified as a flow regime-based phenomenological model (Lahey, 1986). This solution is based on the "branch region of influence" hypothesis, similar to that presented by Azzopardi and Whalley in (1982), and, from a formal point of view, it can be handled as a single one, both for upward and downward branches.

By using a similar approach, one more single solution has been found for lateral branches, also this one formally valid both for liquid entrainment and for gas pull-through (Castiglia and Giardina, 2002).

Implementing the model in RELAP5/MF code (a Multi Fluid version of the well known RELAP5 code series) (Franchello et al., 1993), which doesn't incorporate stratification-entrainment modelling capability, a large number of experimental data have been successfully reproduced. The data refer to a wide range of branch to main pipe diameter ratios and different main pipe pressures.

2. Model outlines

Referring the readers to previous papers for the cases of upward and downward branches, here we will confine to briefly outline the model for the case of lateral branch, making reference to a horizontal, large diameter, main pipe with a lateral branch perpendicularly attached to the wall, where stratified two-phase flow in steady state condition occurs (Fig.s 1a and 1b). The h parameter represents the distance of the gas-liquid interface from the branch axis, whereas h_{bl} and h_{bg} values represent the critical distances at the beginning of liquid entrainment or of gas pull-through, respectively.

On the basis of what said in the previous section, the model relies on the idea that, when liquid or gas entrainment processes occur, there is some "region of branch influence" from which the liquid and the gas are withdrawn. The rest of liquid and gas in the main pipe unaffected by the entrainment in the "region of influence", exits the test section through the run section.

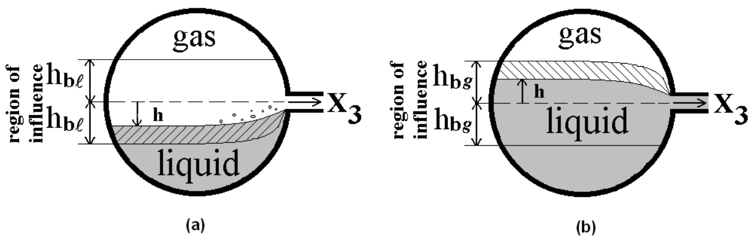

Fig. 1. Lateral branch: (a) liquid entrainment; (b) gas pull-through.

The Azzopardi and Whalley idea (1982), referred to annular flow regime. Consequently, here, the "region of branch influence" concept will be handled in a different way, as it will be shown in the following.

We devised to consider as "region of branch influence" the one delimited by the horizontal levels at distance h_{bi} above and below the horizontal plane of the branch axis ($i \equiv \ell$ for liquid entrainment; $i \equiv g$, for gas pull-through: see Fig.s 1a and 1b).

Taking into consideration these assumptions, the proposed model proceeds by simple geometrical considerations. Indeed, at first glance we hypothesize that the void and the liquid fractions, needed for the calculation of the mass flow entering the branch, are a power function of the volumes fraction taken up by the gas and by the liquid in the region of branch influence. What's more, for sake of simplification, these volumes, are put as the gas and the liquid layers in the region of influence whose thicknesses are well established and whose length can be assumed as unlimited along the main pipe axis, if the branch diameter is small enough that the point sink hypothesis can be adopted (Craya, 1949). Consequently, we propose to cast all the above mentioned quantities in the following functional form:

$$\frac{\alpha_3}{1-\alpha_3} = \frac{1}{k_1}\left(\frac{h_{bi}+h}{h_{bi}-h}\right)^{\frac{1}{n}} \qquad (1)$$

where α_3 is assumed to be the void fraction of the flow entering the branch, and k_1, and n, are no dimensional constants. Introducing in Eq. (1) the slip fraction, needed to change from void fraction to quality, and working with some algebra, it is possible to deduce the parameter $r = h/h_{bi}$ as function of the branch exit quality, x_3, i.e:

$$r = \frac{k_2 x_3^{\,n} - (1-x_3)^n}{k_2 x_3^n + (1-x_3)^n} \qquad (2)$$

where $k_2 = (k_1\, \rho_\ell / S\, \rho_g)^n$, S being the slip ratio. In the above equation the slip ratio was, tentatively, assumed as function of the pressure only (Fauske, 1962; Moody, 1965; Castiglia et al., 1979). Obviously, other slip formulations can be adopted, with consequent loss of simplicity.

For the evaluation of the parameter h_{bi}, which appears in Eq.s (1) and (2), the Craya expression as modified in (Smoglie et al., 1987) has been adopted, i.e.:

$$h_{bi} = \frac{k^*\, w_{i3}^{0.4}}{[g\, \rho_i\, (\rho_\ell - \rho_g)]^{0.2}} \qquad (3)$$

here, ρ_i and w_{i3} are used for the mass density and the mass flow rate of the continuous phase (gas phase for liquid entrainment and liquid phase for gas pull-through, respectively).

Finally, for k* it is assumed the constant value of 0.69 for liquid entrainment and of 0.75 for gas pull-through, as proposed in (Smoglie et al., 1987) on the basis of their experiments.

2.1 Determination of the k_2 and n model parameters

The parameters k_2 and n have been empirically determined by fitting Eq. (2) to experiments reported in literature taking into account various operating pressure ranges. In particular, we employed the experiments performed at UCB (University of California at Berkeley) by Schrock et al. (1986), and at KfK by Reimann and Smoglie (1983), as well by Smoglie et al. (1987), which refer to branches of different diameters, various test pressures in the range 0.15÷ 0.8 MPa and various flow regimes different from the purely stratified one (stratified-waves, high waves-slug, plug, and developed slugging flow), grouped all together (Fig.2). The fitting procedure yielded the following values:

$$k_2 = 0.16;\ n = -0.74 \tag{4}$$

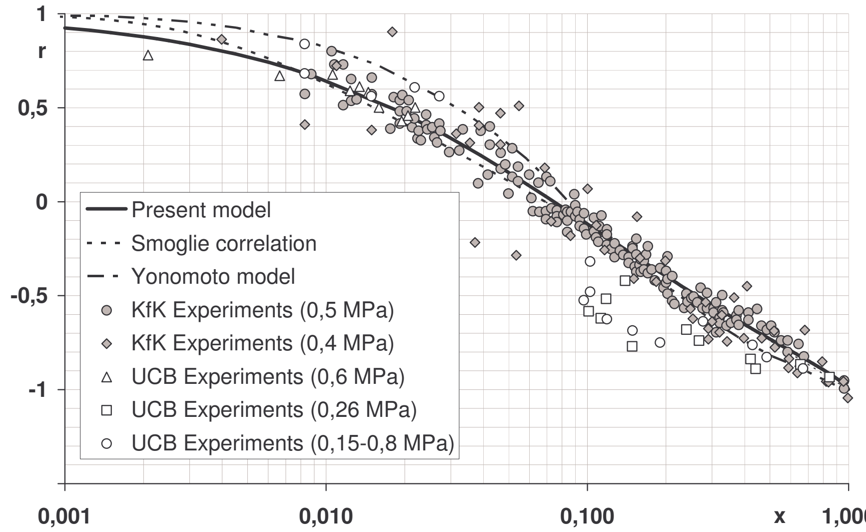

Fig. 2. Comparison between Eq. (2), where the parameters Eq. (4) are used, with KfK and UCB experiments for lateral branch.

Note that in lateral branch experiments, the h parameter is assumed to be different in sign on whether the gas-liquid interface level falls above or below the branch axis. Therefore the normalized interface level r varies in the range $-1 \le r = h/h_b \le 1$. This allows Eq. (2) to really be a single one, regardless liquid entrainment or gas pull through takes place.

Fig. 2 also shows the comparison among the Eq. (2) results, where the above fitting constant values (4) are used (solid line) and the expressions obtained by Smoglie et al. (1987) (dotted line) and Yonomoto and Tasaka (1988) (dotted and dashed line). As one sees, our model and Smoglie correlation show very good results with respect to the Yonomoto model.

3. CORRELATION OF EXPERIMENTAL DATA

The modified and no modified RELAP5/MF code has been used to simulate a large number of experiments presented by Walter et al. (1998) and by Collier (1975).

The Walter experiments were carried out by using air-water mixture flows at pressure of 150 ± 10 kPa and near-ambient temperature. The test section consisted of a horizontal main pipe, 0.0381 m inner diameter, and lateral branches characterized by diameters ratios D_3/D_1 = 0.206 and 0.5. The experiments consist by different groups, each characterized by fixed inlet conditions and variable discharged rates. Stratified and stratified-wavy flow regimes were observed. Table 4 reports the experimental group identification number, the ratio D_3/D_1, the liquid and gas mass flows entering the main pipe (G_{l1}, G_{g1}) and the inlet quality, x_1.

Table 4. Experiments performed by Walter et Al.

Experiments	D_3/D_1	G_{l1} [kg/s]	G_{g1} [kg/s]	x_1
n° 2	0.5	0.0105	$5.37x10^{-3}$	0.338
n° 3	0.5	0.0441	$5.57x10^{-3}$	0.107
n° 9	0.5	0.0441	$2.17x10^{-2}$	0.323
n° 18	0.206	0.0453	$5.63x10^{-3}$	0.108

In Fig.s 3 through 6 the experimental data (points) are compared with the results obtained by using modified and no-modified RELAP5/MF code (thick solid line and thin solid line, respectively). These results are represented in terms of ratio of flow quality in the branch to flow quality in the main pipe, x_3/x_1, as function of ratio of flow entering the branch to the total flow, G_3/G_1. Also in these Figures, the experimental uncertainty on the ratio x_3/x_1, found by Authors to remain within $\pm$ 15% (Collier, 1975), is marked.

The agreement between the model results and the experimental data appears to be quite good. In fact, the model predicts all the experiments with deviations well below to the ones declared by the Authors, but for the experiments relevant D_3/D_1=0.206, where, anyway the disagreement decreases as the G_3/G_1 ratio increases (Fig. 6).

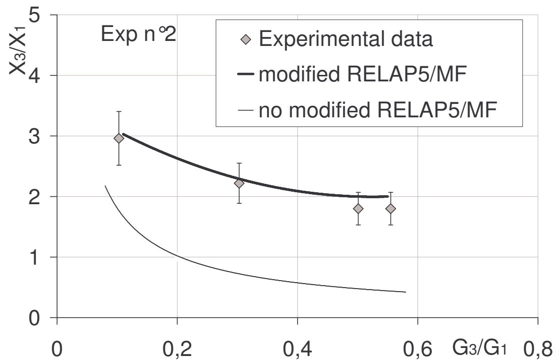

Fig. 3. Comparison between model results and experiments (Exp. n°2).

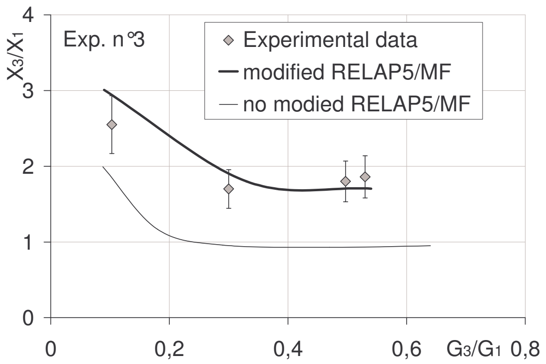

Fig. 4. Comparison between model results and experiments (Exp. n°3).

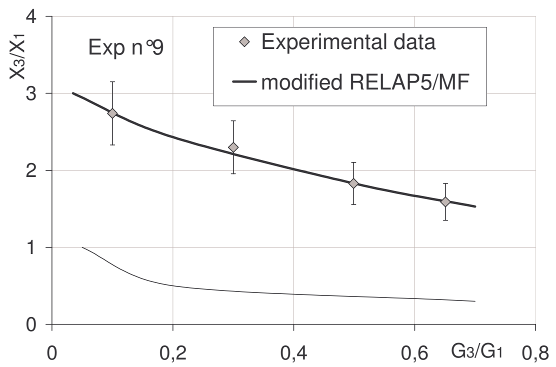

Fig. 5. Comparison between model results and experiments (Exp. n°9).

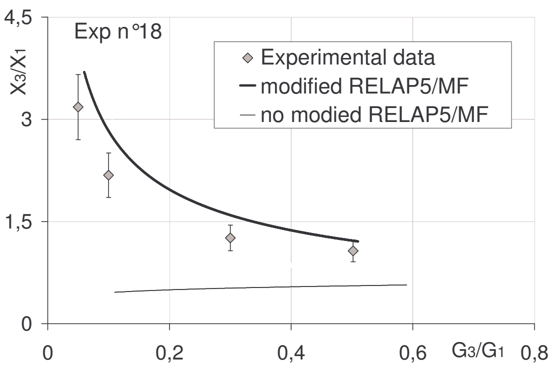

Fig. 6. Comparison between model results and experiments (Exp. n°18).

The experiments presented by Collier were performed by using a test section consisting of a horizontal main pipe, 0.0381 m inner diameter, and a lateral branch characterized by the diameters ratio $D_3/D_1 = 0.65$. A single value of the inlet quality has been used for each series of experiments.

Table 5 reports the experimental liquid and gas mass flows entering the main pipe (G_{l1}, G_{g1}) and the inlet quality, x_1.

Table 5. Experiments performed by Collier

Experiments	$G_{\ell 1}$ [kg/s]	G_{g1} [kg/s]	x_1
Test 1	0.0769	0.0769	0.5
Test 2	0.0892	0.0646	0.42
Test 3	0.103	0.0508	0.33
Test 4	0.11535	0.03845	0.25
Test 5	0.1276	0.0262	0.17
Test 6	0.14734	0.00646	0.042

This time, the experimental data are represented in terms of ratio of liquid mass flow in the branch to liquid mass flow in the main pipe, G_{l3}/G_{l1}, as function of ratio of gas mass flow entering the branch to gas mass flow in the main pipe, G_{g3}/G_{g1}. In Fig.s 7 through 12 the comparisons between the results obtained by using modified and no-modified RELAP5/MF code (again, thick solid line and thin solid line, respectively), and the experimental data (points) are shown. One sees that, also in this case, all the obtained results show a remarkable model predictions capability, but for the Test 6 (Fig. 12) where however a very low disagreement takes place.

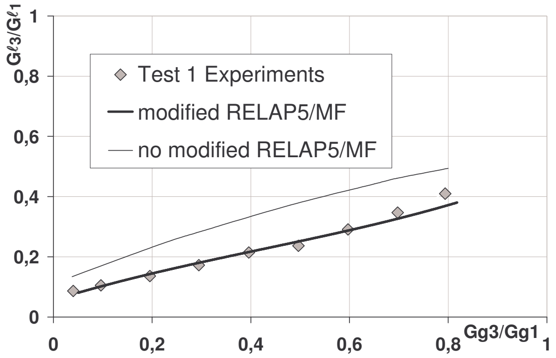

Fig. 7. Comparison between model results and Test1 experiments.

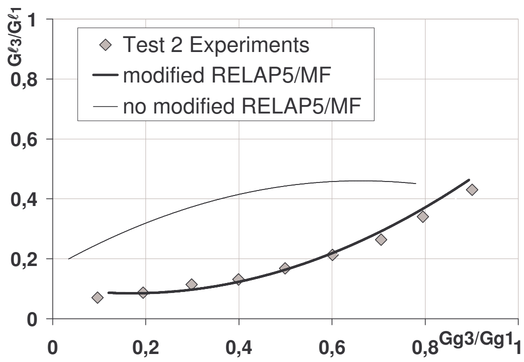

Fig. 8. Comparison between model results and Test2 experiments.

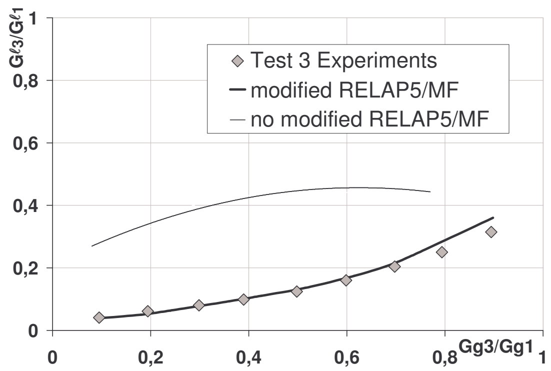

Fig. 9. Comparison between model results and Test3 experiments.

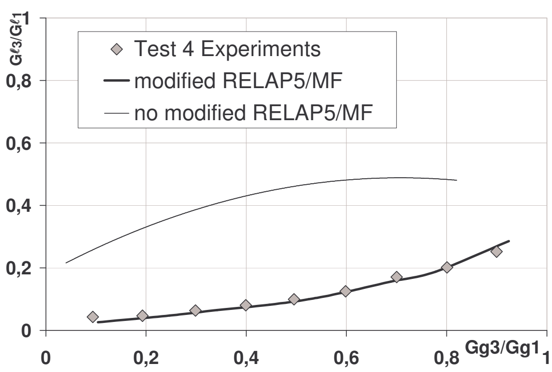

Fig. 10. Comparison between model results and Test4 experiments.

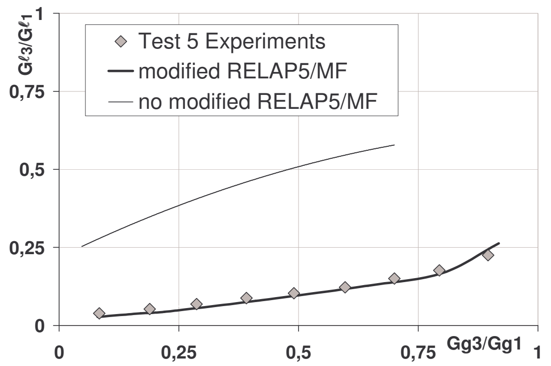

Fig. 11. Comparison between model results and Test5 experiments.

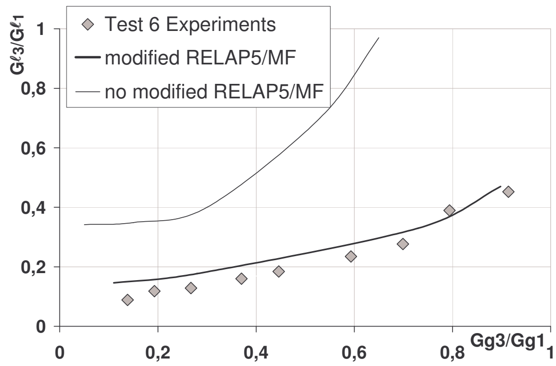

Fig. 12. Comparison between model results and Test6 experiments.

4. CONCLUSION

After previous studies relevant the phenomena involved in two-phase flows subdivision in upward, downward branches, connected to a large horizontal main pipe, which resulted in the proposal of a semi-theoretical model, here we report an extension of this model also to the case of lateral branches and we test it as regards its capability to predict a lot of experimental data of literature performed at KfK, UCB, as well by Walter and Collier.

As this regard, various forms have been used to represent the experimental data, i.e.: $r = h/h_b$ parameter as function of the exit quality, x_3; ratio of flow quality in the branch to flow quality in the main pipe, x_3/x_1, as function of ratio of flow entering the branch to total flow, G_3/G_1; and, finally, ratio of liquid mass flow in the branch to liquid mass flow in the main pipe, G_{l3}/G_{l1}, as function of ratio of gas mass flow entering the branch to gas mass flow in the main pipe, G_{g3}/G_{g1}.

The inspection of the performed comparisons shows a good model performance. Moreover, comparison among our model prediction and those relevant the most quoted models proposed by other Authors (Fig. 2), evidences that such a model proves to be capable to capture the essence of the phenomenologies involved in phases subdivision through branching conduits with various forms of separated flows regimes in the main pipe.

The model is simple to be handled and suitable to be implemented as subroutine in most of the existing thermal-hydraulic codes.

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