

ON THE STRATIFICATION CRITERION IN THE CATHARE CODE

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Abstract

In the CATHARE code, the stratification criteria consider both the stability of the stratified flow regime and the stability of a bubbly flow. This paper focuses on the transition from bubbly to stratified flow. It can be modelled by considering the balance between buoyancy that induces bubbles to rise and accumulation of gas phase at top of the pipe and turbulence that mixes bubbles. A ratio of a turbulent velocity to a free bubble rise velocity is used to determine the flow regime. A new model is proposed based on METERO test data which may reduce code uncertainty.

Introduction

This work is part of the NEPTUNE project developed jointly by EDF, CEA, AREVA and IRSN. A new Multi-scale simulation platform is developed and validated for nuclear reactor thermal-hydraulics including the new system code CATHARE-3 [1]. Among its new capabilities, it provides additional transport equations for interfacial area and for turbulent scales. One of the applications for such a new model is the improvement of the flow regime transitions since turbulence influences the flow structure as shown in vertical bubbly flow [2]. Specifically, this paper deals with the transition from bubbly to stratified flow.

The knowledge of the flow regime in horizontal pipes may play an important role in PWR accident scenarios. For example, during many LOCA transients, the flow regime in Hot Legs or Cold Legs influences the amount of liquid and steam either lost at a break or entrained in the pressurizer surge line (in case of a pressure relief valve opening). Both the primary mass inventory and the primary pressure are very sensitive to the steam quality at the break or at the open relief valve. In particular, the quality of the flow rate at a pressurizer relief valve will strongly depend on the flow regime at the T junction, as illustrated in Figure 1 and Figure 2.

In horizontal flow, CATHARE is able to consider two established flows: the fully stratified flow and the fully non-stratified flow with an intermediate flow between them. The transition from stratified to non stratified flow is described using Kelvin Helmholtz instability but this paper concentrates on the bubbly to stratified flow. It can be modelled by considering a balance between turbulence and buoyancy effects. Buoyancy induces bubbles to rise and promotes coalescence while turbulence mixes bubbles preventing them from rising. A ratio of a turbulent velocity scale to a free bubble rise velocity can be used to determine the flow regime: the flow remains bubbly for high values of this ratio and stratified for low values. In CATHARE-3, the turbulence velocity can be calculated by a transport equation or evaluated by an algebraic model. The bubble rise velocity can be estimated by a balance between the drag force and the buoyancy force.

As part of the NEPTUNE project, the METERO experiment has been designed to investigate horizontal two-phase flows and particularly transition from bubbly to slug and/or stratified flow. Visualisations of various flow regimes have been realised in METERO and used for the validation of the new transition criteria.

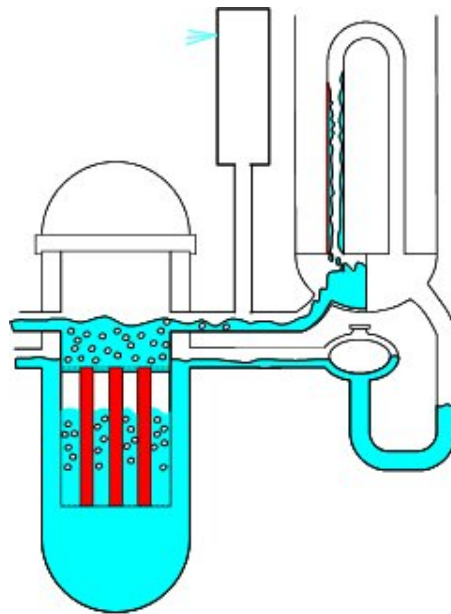


Figure 1 Example of water repartition in a PWR primary circuit during a LOCA

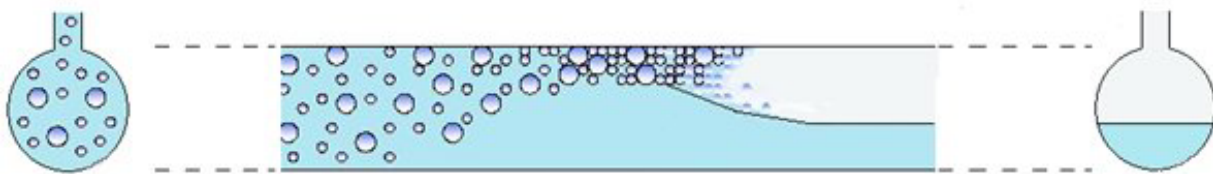


Figure 2 Two different flow regimes at the pressurizer T junction.

1. Stratification criteria of the CATHARE 2 code

In CATHARE code, the horizontal flow map is very simple (full description of the physical laws is given by Bestion [3]). The flow is stratified when two conditions are satisfied:

- The stratified flow is stable with respect to Kelvin-Helmholtz instability ($R1=1$)
- The bubbly flow is not stable and phase separation may occur ($R2=1$)

The rate of stratification:

$$R = R2 \cdot R1 \quad (1)$$

is equal to 1 in pure stratified flow and to zero in fully non-stratified flow.

$R1$ corresponds to a Kelvin-Helmholtz instability (see de Crecy, [4] and Bestion et al., [5]) and is calculated using the Froude number:

$$Fr = \frac{\rho_v \rho_l (V_v - V_l)^2}{g(\rho_l - \rho_v) \rho_m D_H} \quad (2)$$

$R1$ is equal to 1 when $Fr > 0.25$ and equal to zero when $Fr > 1$

The stability of the bubbly flow depends on the ratio V_t/V_b of a turbulent velocity to a bubble rise velocity. R2 is equal to zero for a stable bubbly flow and zero for an unstable bubbly flow. The flow regime is calculated as follows:

	R1	R2	$R = R1.R2$	Flow regime
Stable stratification Unstable bubbly	$R1=1$	$R2=1$	$R=1$	Stratified
Unstable stratification Unstable bubbly	$R1=0$	$R2=1$	$R=0$	Non-stratified
Unstable stratification Stable bubbly	$R1=1$	$R2=0$	$R=0$	Non-stratified
Stable stratification Stable bubbly	$R1=0$	$R2=0$	$R=0$	Non-stratified

Table 1 CATHARE horizontal flow stratification criteria.

It can be seen that in the fourth case it is not possible to conclude on the flow regime since both bubbly and stratified flow are stable. In this case, the present criterion predicts a non-stratified flow although a bubbly flow may also exist depending on the previous upstream flow regime. The two sub-indicators R1 and R2 are local algebraic quantities and thus have no memory of their previous or upstream values so the code does not know the evolution of the flow regime. The transport of interfacial area concentration (denoted IA in the text) would probably be sufficient to indicate if bubbles exist (high order of magnitude for IA). A four-field model with a continuous gas field and a dispersed gas (bubbles) field would keep the history of the flow structure and would allow a description of the transition dynamics. The development of such advanced models is part of the long term research in the NEPTUNE project and will not be described here.

In a horizontal bubbly two-phase flow, where the density ratio is not negligible, gravity/buoyancy tends to separate the phases: the bubbles tend to rise toward the top of the pipe, then to coalesce creating large gas inclusions that will merge leading later to stratified flow. The turbulent dispersion tends to mix liquid and gas thereby maintaining bubbly flow. The persistence of the dispersed flow will strongly depend on the liquid turbulence intensity.

Three forces are in balance for the evolution of bubbles: buoyancy, drag and turbulence dispersion which depends on vertical void gradient. Since turbulence dispersion cannot be expressed in a 1D model, it is quite difficult to write a balance equation for these three forces. A more simple way consists in comparing two velocities: V_b the bubble rise velocity and V_t the turbulent one. We consider that the flow will remain bubbly if $V_t \gg V_b$ or will stratify if $V_b \gg V_t$. After modelling the two velocities, threshold values for the ratio of the velocities have to be set in order to define the transition criteria corresponding to the different flow regime limits.

In the current industrial version, namely CATHARE-2, the velocities have been defined as follows.

The terminal velocity of a bubble in an infinite medium at rest is obtained by balancing drag (right hand side) and buoyancy (left hand side) forces:

$$\frac{1}{6}\delta^3\pi g(\rho_L - \rho_g) = \frac{1}{8}\pi\delta^2 C_d \rho_L V_b^2 \quad (3)$$

The velocity is then:

$$V_b = \sqrt{\frac{4}{3} \delta \frac{g(\rho_L - \rho_g)}{C_d \rho_L}} \quad (4)$$

For reasons of simplicity, the distorted bubbly coefficient has been chosen (Ishii, 1979):

$$C_d = \frac{2}{3} \frac{\delta}{\mathcal{E}} \quad (5)$$

Where $\mathcal{E}$ is the Laplace (capillarity) scale.

The main advantage of this choice is that the bubble diameter completely disappears from the bubble velocity expression as it has been replaced by the Laplace scale:

$$V_b = \sqrt{2\mathcal{E} \frac{g(\rho_L - \rho_g)}{\rho_L}} \quad (6)$$

To generalise the velocity to all types of bubbles, various correlations for the drag coefficient should be used (as given by Ishii, 1979, for example). But the bubble diameter would become an unknown of the problem. One possibility to calculate this diameter would be to use an IA transport equation and assume that all the bubbles have the same size. Since such IA equation is not yet available, the expression for the bubble rise velocity is:

$$V_b = \left(\frac{4\sigma g(\rho_L - \rho_g)}{\rho_L^2} \right)^{1/4} \quad (7)$$

In CATHARE 2, it was considered that the turbulent liquid velocity is proportional to a friction velocity:

$$V_t \approx V_f = \sqrt{\frac{\tau_{wL}}{\rho_L}} = \sqrt{\frac{C_f}{2}} V_L \quad (8)$$

Using a constant friction coefficient corresponding to the lowest limit in CATHARE friction model:

$$C_f = 0.003$$

The ratio of these velocities reads:

$$\frac{V_t}{V_b} = C \left| V_L \left(\frac{\sigma g \Delta \rho}{\rho_L^2} \right)^{-1/4} \right| = 0.0275 \left| V_L \left(\frac{\sigma g \Delta \rho}{\rho_L^2} \right)^{-1/4} \right| = 0.0275 V^* \quad (9)$$

with

$$V^* = \left| V_L \left(\frac{\sigma g \Delta \rho}{\rho_L^2} \right)^{-1/4} \right| \quad (10)$$

The determination of the threshold was based on the Super Moby-Dick (SMD) experimental results (Memponteil [6]). SMD is an 80's experimental pressurised facility (2 to 10 Mpa) with a 80mm inner diameter horizontal test section (see Figure 3). This facility investigated stratification occurrence depending on mass flow rate, quality and pressure. A 30-beam X-ray densitometer was used to obtain vertical profiles of density. Examples of typical profiles are given on Figure 4. Averaged void fractions as well as collapsed levels H_c were obtained using data processing. The parameter C_{STRAT} representative of the stratification in the test section was also calculated:

$$C_{STRAT} = \frac{\rho^- - \rho^+}{\rho_L - \rho_V} \quad (11)$$

ρ^- and ρ^+ are respectively the averaged density below and above H_c calculated using measured density profiles. For a uniform density profile C_{STRAT} will approach zero. For a stratified smooth flow pattern it will be nearly equal to 1; as there is always some scatter in the data due to noise and inaccuracy of the apparatus, the value 1 was never reached exactly.

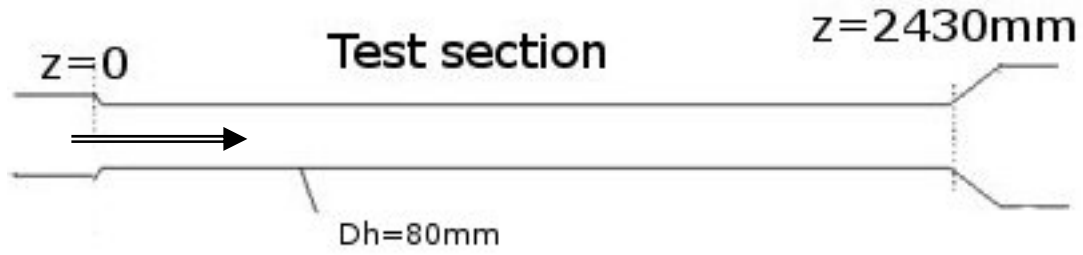


Figure 3 Super Moby-Dick test section.

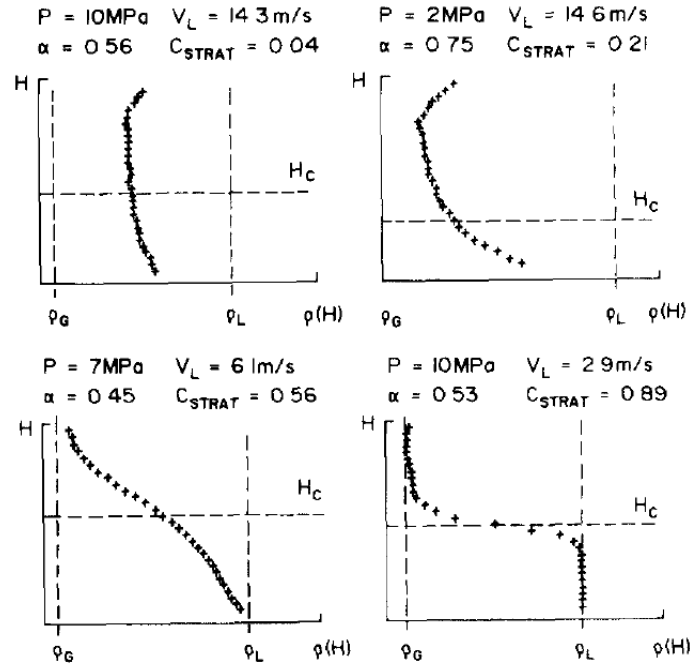


Figure 4 Examples of density profile measurements performed in the SUPER MOBY DICK horizontal test section (top-left is nearly homogeneous, bottom right looks stratified-wavy, the other being intermediate)

As illustrated in Figure 5, the experimental stratification rate C_{STRAT} is well correlated with the dimensionless velocity V^* . The thresholds between stratified and non-stratified flows were obtained from previous data. They are given in Table 2.

R_2			
$V^* < V_{inf}^*$	$V_t < 1.1 V_b$	$R_2 = 1$	Stratified flow
$V_{inf}^* < V^* < V_{sup}^*$	$1.1 < V_t/V_b < 2.5$	$R_2 = 1 - \left\{ \frac{(V^* - V_{inf}^*)^2}{(V_{sup}^* - V_{inf}^*)^3} (3(V_{sup}^* - V_{inf}^*) - 2(V^* - V_{inf}^*)) \right\}$	Transition
$V^* > V_{sup}^*$	$V_t > 2.5 V_b$	$R_2 = 0$	Non-stratified flow

Table 2 Thresholds for non-stratified to stratified flow

The thresholds are: $V_{inf}^* = 40$ and $V_{sup}^* = 90$

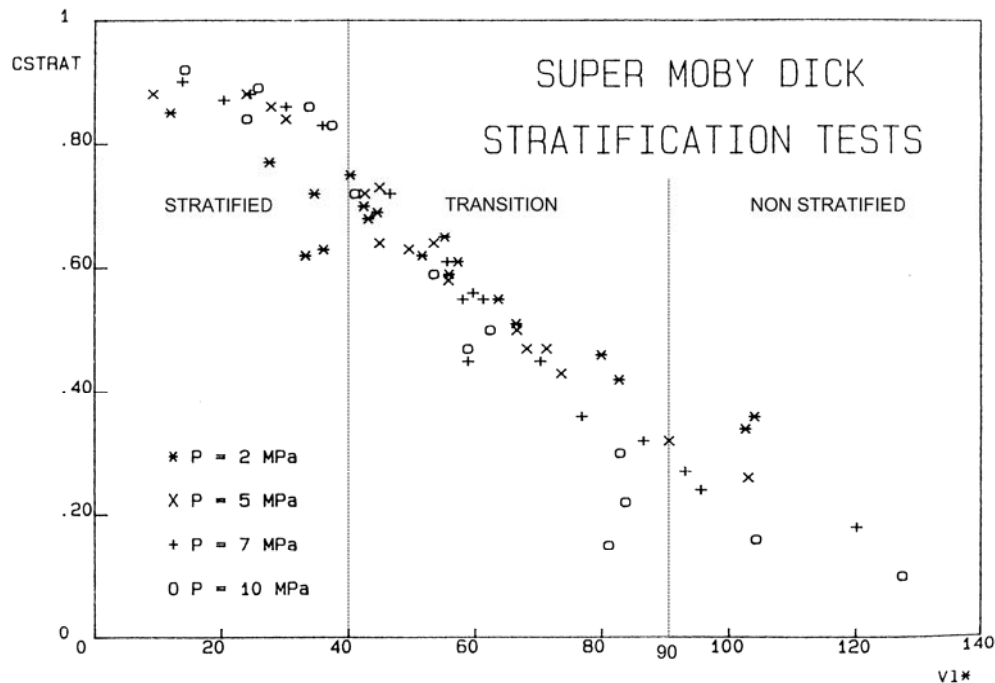


Figure 5 SMD stratification rate C_{STRAT} versus dimensionless velocity V^* .

2. Flow map obtained from METERO – Comparison with CATHARE-2 criterion.

2.1 Description of the facility

2.1.1 Overview of the facility

The experiment is made of stainless steel pipes linked to a Plexiglas® test section (Figure 6). Two independent air and water supply circuits merge upstream of the test section through an injection/tranquilization system. This system provides a horizontal two-phase flow at the inlet of the test section. At the test section outlet, water and air are separated in a 1500 liters storage tank. The water temperature is kept constant (around 18° C) by means of a heat exchanger located inside the tank. The main characteristics of the installation are summarized in Table 3. All the flow parameters can be controlled and/or acquired directly from the control/command room, via a personal computer and use of LabviewTM programs. These programs also pilot the instrumentation data acquisition.

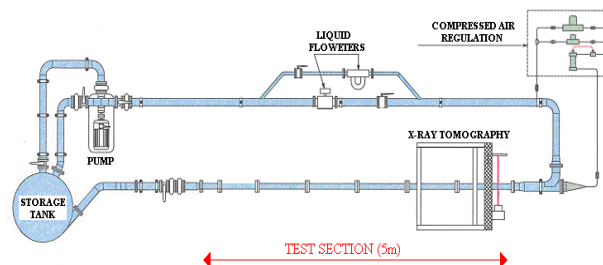


Figure 6 Schematic diagram of METERO.

Inlet temperature air-water	18°C
Maximum outlet temperature	20°C
Maximum driving pressure	2.8 bar
Water flow rate	0 to 150 m ³ /h.
Water velocity	0 to 5 m/s
Air mass flow rate	0 to 350 l/mn
Air superficial velocity	0 to 0.7 m/s

Table 3 METERO main parameters

2.1.2 Water supply – flowrate measurements

Concerning water supply, the circuit is composed by a FinderTM pump, of driving pressure 2.8 bar, maximum flowrate 150 m³/h (which corresponds to a maximum water velocity of 5.5 m/s) linked to the test section by means of two lines including a flowmeter, a 1 inch line for the scale 0 to 15 m³/h and a 4 inches line for the scale 15 to 150 m³/h. For the small flowrates (0-15 m³/h), a YokogawaTM Coriolis mass flowmeter is used (accuracy about 0.2 % of the measurement point). For the higher flowrates (15 to 150 m³/h), a KrohneTM electromagnetic volumic flowmeter is installed. It offers a lower accuracy than the Coriolis flowmeter but generates also reduced pressure drop. The inlet water temperature is measured by a type K standard thermocouple with a +/-0.5°C measurement accuracy. This accuracy revealed inadequate for hot film anemometry, very sensitive to flow temperature variations. The thermocouple was then calibrated using a calibration bath and a platinum PT100 sensor.

2.1.3 Air supply – flowrate measurements

Concerning the air supply, it is composed of a 6 bar pressure supply line involving a depressurization/filtration system and two lines of regulation and measurement of the mass flowrate: one line for the range 0 to 50 l/mn and a second line for the range 50 to 350 l/mn, corresponding to a maximum gas velocity of 0.7 m/s. The air circuit is open: after being separated from the water in the tank, the air is vented to the atmosphere. The two flowmeters are Brooks EmersonTM thermal massic flowmeters (accuracy is 0.7 % of the measurement point). They include a PID regulation system that provides steady inlet conditions and easy use. The air temperature is measured by a type K thermocouple, with a measurement accuracy of +/-0.5°C.

2.1.4 Pressure measurements

The inlet and outlet pressures are measured by means of two KellerTM high precision membrane sensors. They measure the pressure relative to the atmosphere in the range 0-3 bar with an accuracy of +/- 0.015% of the full scale, i.e. +/- 0.45 mbar.

2.1.5 Test section

The test section, 5.40 m in length, has an inner diameter of 0.1 m. It is composed of interchangeable and rotating sections including instrumentation modules. The inlet injection/tranquilization system is made of 320 tubes for the water and 37 for the air. The number and dimensions of the tubes have been set by iterative tests. The air bubbles injection is made uniformly in the inlet section. The void

fraction, directly depending on the number of bubbles injected, is modified by varying the air mass flowrate. The system also includes a series of grids designed to break remaining vortices generated by upstream elbows and then ensure a low turbulence level -the *so-called* grid turbulence- at the inlet of the test section. Moreover, a grid located 3 diameters away from the injectors mixes the liquid and a gas phase so as to avoid the signature of injector wakes on the velocity profiles and ensure uniform bubble distribution.

2.2 Visualization of the flow regime

2.2.1 Fast camera videos

Two numerical Photron Fastcam SA01 and SA03 cameras have been used for the visualizations. Their detection matrix size is 1024*1024 pixels². The sampling frequency is 5400 images per second full format for the SA1 camera and 2000 images /sec for the SA3. The shutter speed can be set up to 1/10 000 s. Different photographic lenses have been used (focal length ranging from 28 to 105 mm). The scene lightning (see Figure 7) was obtained by use of two DEDOLIGHT 575 W spotlights. The software PFV ensures the adjustment of the camera parameters and the acquisition of the videos. The camera is placed so as to acquire a side view of the pipe and a 45° mirror is clamped above the test section to provide top and side view of the flow in the same time.

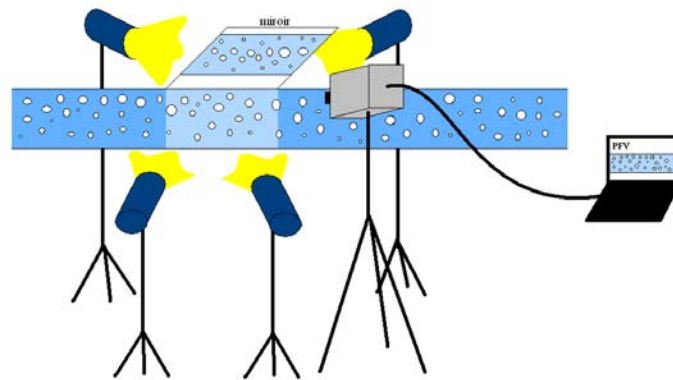


Figure 7 flow visualization

2.2.2 Flow pattern

The flow map obtained from the visualization realised on METERO and the results obtained from the CATHARE-2 criterion are given on Figure 8. The stratified bubble flow regime was added to the classical list of flow regimes. It corresponds to bubbles which are mostly in the upper part of the flow whereas in the “dispersed bubbly” flow, bubbles are more uniformly distributed. As shown in the previous figure, the intermediate flow regime zone (located between R=0 and R=1) is too large and it is mainly due to the R=0 transition curve located at very high liquid superficial velocities. The R2=0 curve shows that this discrepancy comes from the R2 model. Thanks to the instantaneous velocity measurements performed in METERO, it is possible to calculate turbulent kinetic energy and then to check whether the turbulent velocity scale model (eq. 8) that is used to calculate R2, is correct or not. The experimental turbulent velocity scale is defined as follows:

$$V_T = \sqrt{\frac{2}{3}k} \quad (12)$$

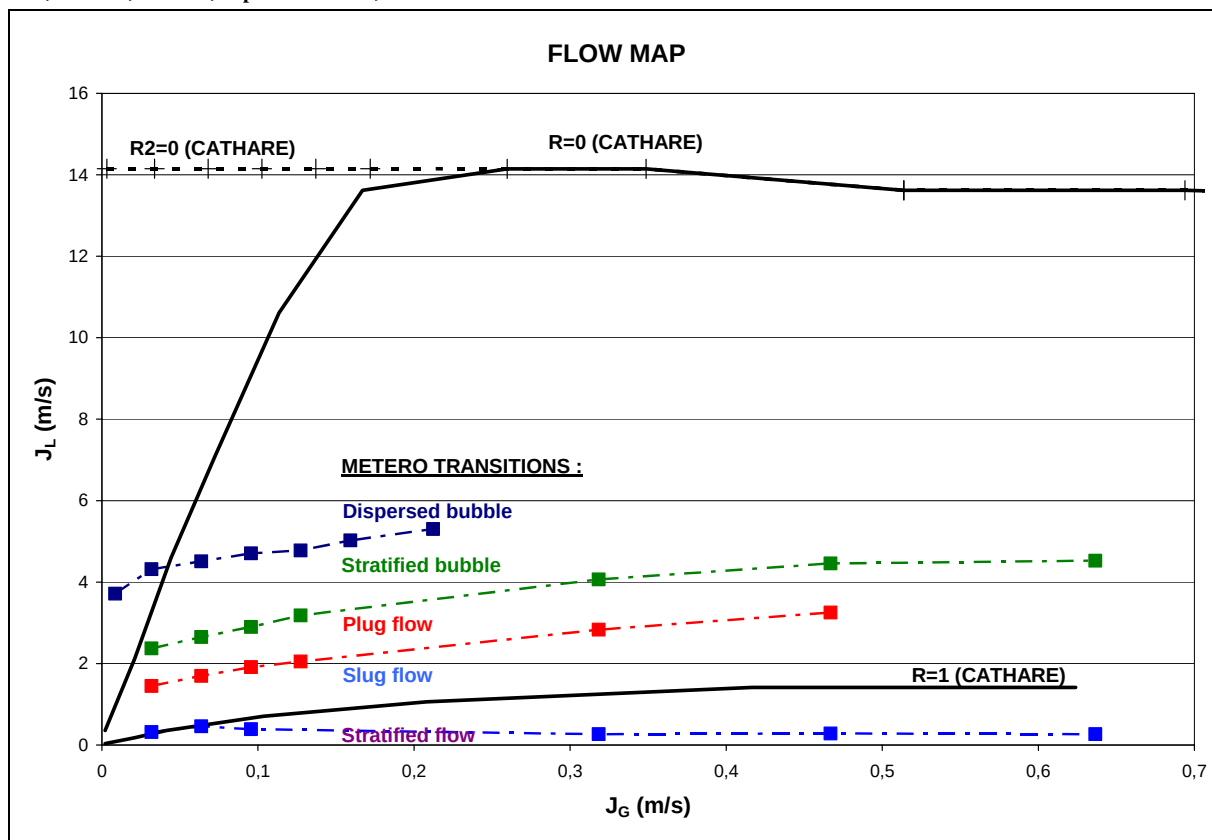


Figure 8 METERO - CATHARE-2 flow map

Where k is the spatially averaged turbulent kinetic energy.

In bubbly flow, the METERO test corresponding to $J_L = 4.42 \text{ m/s}$ [8] and $0 \leq J_G (\text{m/s}) \leq 0.13$ is used. In the last section where the flow is nearly established, the spatially averaged turbulent kinetic energy ranks as follows depending on J_G values (the highest value of k corresponds to the highest value of J_G): $0.15 \leq k (\text{m}^2/\text{s}^2) \leq 0.2$. Thus, the corresponding turbulent velocity scale ranks: $0.3 \leq V_T (\text{m/s}) \leq 0.36$. From equation (8), the turbulent velocity scale estimated by the model ranks: $0.17 \leq V_t (\text{m/s}) \leq 0.18$ (liquid velocities have been calculated with CATHARE code). Thus, model underestimates the turbulent velocity scale and thereby V^* , by a factor two in METERO bubbly flow. It explains that the $R=0$ transition curve is located at too high liquid velocity.

This discrepancy has to be relativised since it appears only in an atmospheric air-water experiment (METERO) and not in high pressure steam-water experiment (SMD). An improvement of the transition criterion is obtained using METERO results and then verified using SMD results.

3. A new model for transition from bubbly to stratified flows

The turbulent velocity scale in the standard model depends only on the mean velocity since the friction coefficient is taken as constant. Thereby, it cannot take into account the real level of turbulence that depends on both the Reynolds number and the geometry (e.g. a singularity in the flow can increase drastically this level). Thus, one possible way to improve the current criterion is to use a turbulence model to calculate more precisely the turbulent velocity scale. In the Neptune project, an original turbulence model has been developed for the CATHARE-3 code. Two versions are available: an algebraic version [7] which gives the turbulent kinetic energy k for established single-phase flows and a transport equation model ([2]) which gives both k and the dissipation rate ε . In horizontal bubbly

flows, the spatially averaged turbulent kinetic energy (usable in 1D calculations) obtained from METERO experiment has shown that the part of turbulence produced in the wall shear layers (single phase flow effect) is much larger than the part induced by the motion of bubbles [8]. The reason is that, in horizontal flow, the axial slip velocity is very small. Therefore, the single-phase flow algebraic model is sufficient in this situation as a first approximation, to estimate the level of turbulent kinetic energy.

$$k_{\infty} = C_{1\phi} V_L^2 C_f^{2/3} \quad (13)$$

With: $C_{1\phi} = 0.2$, V_L being the averaged velocity and C_f the friction coefficient.

The new turbulent velocity scale becomes:

$$V_t = \sqrt{\frac{2}{3} k_{\infty}} \quad (14)$$

Using this new model one obtains: $V_t(\text{m/s})=0.26\text{m/s}$ for $J_L=4.42\text{m/s}$ tests. This value is rather close to experimental results. More precise results can be obtained using the transport equation turbulence model [7] since it depends on J_G : $0.26 \leq V_t(\text{m/s}) \leq 0.3$. All the following results have been obtained using the algebraic model.

Due to the modification of the turbulent velocity scale model, thresholds for V^* have to be modified (see Table 2). An a priori choice consists in setting the thresholds in a very simple way:

$$V_{\text{inf}}^* = \frac{1}{2} \quad V_{\text{sup}}^* = 2$$

It means that transitions occur when turbulent and bubble velocities are in a ratio of 2. More precise values can be obtained using a comparison with experimental values. The bubble velocity model remains unchanged. Using this new model, encouraging results have been obtained for METERO (Figure 9). The results obtained on SMD (Figure 10) are quite good with the new model for $D_H=135\text{mm}$ tests but not for the $D_H=80\text{mm}$ tests. For these last tests, the value given by the new stratification criterion is clearly underestimated. It comes from the R2 values since the model for R1 remains unchanged. The underestimation of R2 can result either from the V_{sup}^* value (which has not been optimized) or by the lack of precision of the turbulence algebraic model that would overestimate the turbulent velocity scale. Thus, two possible modifications can be carried out: an increase of the V_{sup}^* threshold and the use of the transport equation model instead of algebraic model for the evaluation of turbulent velocity scale. Both solutions will be evaluated.

Further improvements could be obtained by better taking into account the history effect. The transport of interfacial area provides useful information about the flow regime: if it is very low the flow can only be stratified.

The use of a multifield model with two gas fields would transport even more information on the stratification: if a continuous gas field exists, the flow is stratified. If no dispersed gas field exists, it is a pure separate-phase flow and if a dispersed field also exists, it is a stratified flow with bubbles below the free surface. All the evolution from bubbly to stratified flow during the transition process would be better modeled.

4. Conclusion

The recent METERO experimental data have been analysed in order to improve the accuracy of the stratification criterion of the CATHARE code. The modification of the turbulent velocity scale used in the stratification criterion, based on an original turbulence model, has shown the potentiality to improve this criterion. First results obtained on METERO are encouraging, nevertheless the Super Moby-Dick calculations reveal a complex behaviour of the new model: for a set of experimental tests, results have been improved, but they have been partially degraded for another set. Two types of

modification are planned in order to correct this problem: the optimization of the thresholds V_{sup}^* and the use of a more precise turbulence model that is available.

Another modification would be to take into account the history of the flow regime either by transport of interfacial area or by using a multifield approach.

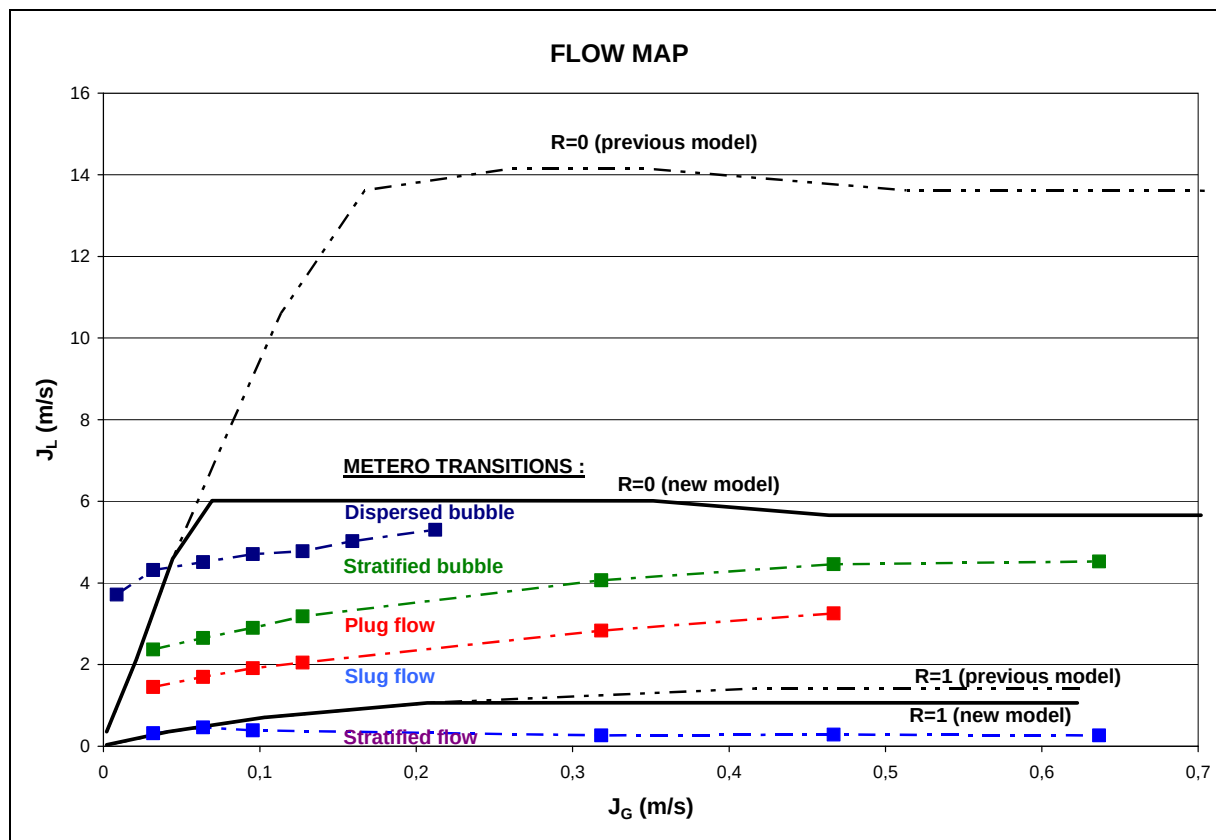


Figure 9 New CATHARE flow map

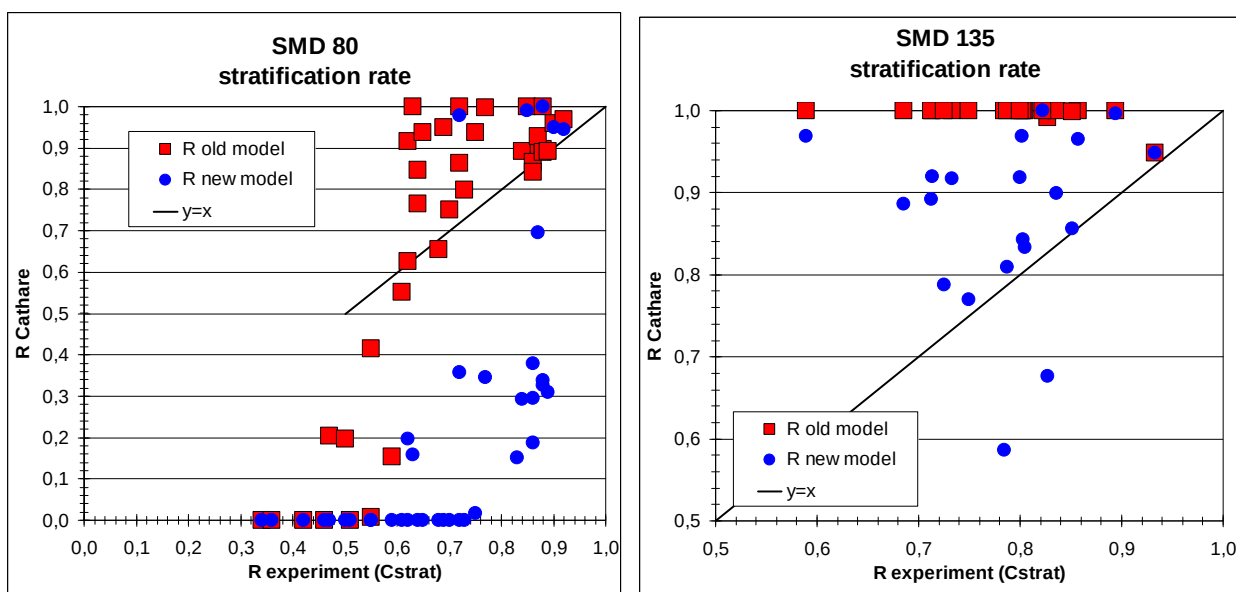


Figure 10 New SMD results (2 diameters: $D_H=80\text{mm}$ and $D_H=135\text{mm}$).

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Nomenclature

C _d	Drag coefficient
D _H	Hydraulic diameter (m)
Fr	Froude number
g	Gravity constant g=9.81m/s ²
IA	Interface area concentration (m ⁻¹)
J	Superficial velocity (m/s)
k	Turbulent kinetic energy (m ² /s ²)
£	Laplace (capillarity) scale: $£ = \sqrt{\sigma/g(\rho_L - \rho_g)}$
Q _G	Gas flowrate (l/mn)
R, R1, R2	Stratification rates
R _e	Reynolds number based on the pipe diameter
u'	Root mean square of the velocity fluctuation (m/s)
V	Velocity (m/s)

Superscript

*	Non dimensional value
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Greek letters

α	Void fraction (-)
δ	Bubble diameter (m)
ρ	Density (kg/m ³)
$\Delta\rho$	Density difference: $\Delta\rho = \rho_L - \rho_G$ (kg/m ³)
σ	Surface tension (N/m ²)
τ	Stress (n/m ²)
ε	Turbulent dissipation rate (m ² /s ³)

Subscripts

b	Bubble
f	friction
g, G	gas
l, L	liquid
m	Averaged (density: $\rho_m = (1 - \alpha)\rho_L + \alpha\rho_G$)
t, T	turbulent
v, V	Vapor
w	Wall
∞	Value taken far from inlet
1 ϕ	Single phase

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