Validation of Advanced Computational Methods for Multiphase Flow

Hervé Lemonnier
Didier Jamet
Olivier Lebaigue

New York • Wallingford, U.K.
Validation of Advanced Computational Methods for Multiphase Flow

Editors:

Hervé Lemonnier, Didier Jamet, and Olivier Lebaigue

Commissariat à l’Energie Atomique
CEA/Grenoble, DER/SSTH
38054 Grenoble Cedex 9, France
Contents

Foreword ix

Preface xi

References xiv

1 Test-case No 1: Rise of a spherical cap bubble in a stagnant liquid (PN) 1

1.1 Practical significance and interest of the test-case 1
1.2 Definitions and model description 2
1.3 Summary of the requested calculations 3
References 4

2 Test-case No 2: Free rise of a liquid inclusion in a stagnant liquid (PN, PE) 7

2.1 Practical significance and interest of the test-case 7
2.2 Definitions and model description 8
2.3 A series of six numerical test-cases 9
2.4 An experimental test-case 12
References 16

3 Test-case No 3: Propagation of pure capillary standing waves (PA) 17

3.1 Practical significance and interest of the test-case 17
3.2 Definitions and model description 18
3.3 A series of test-cases 20
References 21

4 Test-case No 4: Rayleigh-Taylor instability for isothermal, incompressible and non-viscous fluids (PA) 23

4.1 Practical significance and interest of the test-case 23
4.2 Definitions and physical model description 24
4.3 Test-case description 25
References 29

5 Test-case No 5: Oscillation of an inclusion immersed in a quiescent fluid (PA) 31

5.1 Practical significance and interest of the test-case 31
### Test-case No 11: Stretching of a circle in a vortex velocity field (N)

11.1 Practical significance and interest of the test-case
11.2 Definitions and physical model description
11.3 Test-case description
11.4 Example of comparison exercise

References

11 Test-case No 11b: Stretching of a circle in a vortex velocity field

References

### Test-case No 12: Filling of a cubic mould by a viscous jet (PN, PE)

12.1 Practical significance and interest of the test-case
12.2 Definitions and physical model description
12.3 Test-case description
12.4 Figures, tables, captions and references

References

### Test-case No 13: Shock tubes (PA)

13.1 Introduction
13.2 The mathematical model and the solution of the corresponding Riemann Problem
13.3 The shock tube

References

### Test-case No 14: Poiseuille two-phase flow (PA)

14.1 Practical significance and interest of the test-case
14.2 Definitions and physical model description
14.3 Test-case description

References

### Test-case No 15: Phase inversion in a closed box (PC)

15.1 Practical significance and interest of the test-case
15.2 Definitions and physical model description
15.3 Test-case description
15.4 Illustrations of the problem

References

### Test-case No 16: Impact of a drop on a thin film of the same liquid (PE, PA)

16.1 Practical significance and interest of the test case
16.2 Definitions and physical model description
16.3 Test-case description

References

### Test-case No 17: Dam-break flows on dry and wet surfaces (PN, PA, PE)

17.1 Practical significance and interest of the test-case
17.2 Definitions and physical model description
17.3 Test-case description

References
<table>
<thead>
<tr>
<th>Test-case No</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Test-case No 19: Shock-Bubble interaction (PN)</td>
<td>131</td>
</tr>
<tr>
<td>18.1 Introduction</td>
<td>131</td>
</tr>
<tr>
<td>18.2 Description</td>
<td>131</td>
</tr>
<tr>
<td>References</td>
<td>133</td>
</tr>
<tr>
<td>19 Test-case No 21: Gas bubble bursting at a free surface, with jet formation (PN-PE)</td>
<td>135</td>
</tr>
<tr>
<td>19.1 Practical significance and interest of the test-case</td>
<td>135</td>
</tr>
<tr>
<td>19.2 Definitions and physical model description</td>
<td>136</td>
</tr>
<tr>
<td>19.3 Test-case description</td>
<td>138</td>
</tr>
<tr>
<td>References</td>
<td>141</td>
</tr>
<tr>
<td>20 Test-case No 22: Axisymmetric body emerging through a free surface (PE)</td>
<td>143</td>
</tr>
<tr>
<td>20.1 Practical significance and interest of the test-case</td>
<td>143</td>
</tr>
<tr>
<td>20.2 Experimental setup description</td>
<td>144</td>
</tr>
<tr>
<td>20.3 Test-case description</td>
<td>145</td>
</tr>
<tr>
<td>References</td>
<td>148</td>
</tr>
<tr>
<td>21 Test-case No 23: Relative trajectories and collision of two drops in a simple shear flow (PA)</td>
<td>149</td>
</tr>
<tr>
<td>21.1 Practical significance and interest of the benchmark</td>
<td>149</td>
</tr>
<tr>
<td>21.2 Definitions and physical model description</td>
<td>150</td>
</tr>
<tr>
<td>21.3 The description of the benchmark</td>
<td>153</td>
</tr>
<tr>
<td>21.4 Conclusion</td>
<td>154</td>
</tr>
<tr>
<td>References</td>
<td>156</td>
</tr>
<tr>
<td>22 Test-case No 24: Growth of a small bubble immersed in a superheated liquid and its collapse in a subcooled liquid (PE, PA)</td>
<td>157</td>
</tr>
<tr>
<td>22.1 Practical significance and interest of the test-case</td>
<td>157</td>
</tr>
<tr>
<td>22.2 Model and assumptions</td>
<td>158</td>
</tr>
<tr>
<td>22.3 Bubble collapse: case 24-1 (PA)</td>
<td>160</td>
</tr>
<tr>
<td>22.4 Initial stage of the growth of a vapor bubble, case 24-2 (PA)</td>
<td>160</td>
</tr>
<tr>
<td>22.5 Thermally controlled growth of a vapor bubble (24-3)</td>
<td>163</td>
</tr>
<tr>
<td>References</td>
<td>171</td>
</tr>
<tr>
<td>23 Test-case No 26: Droplet impact on hot walls (PA)</td>
<td>173</td>
</tr>
<tr>
<td>23.1 Practical significance and interest of the test-case</td>
<td>173</td>
</tr>
<tr>
<td>23.2 Definitions and physical model description</td>
<td>174</td>
</tr>
<tr>
<td>23.3 Test-case description</td>
<td>175</td>
</tr>
<tr>
<td>23.4 Relevant results for comparison</td>
<td>176</td>
</tr>
<tr>
<td>References</td>
<td>178</td>
</tr>
<tr>
<td>24 Test-case No 27: Interface tracking based on an imposed velocity field in a convergent-divergent channel (PN)</td>
<td>179</td>
</tr>
<tr>
<td>24.1 Practical significance and relevance of the test-case</td>
<td>179</td>
</tr>
<tr>
<td>24.2 Definitions and model description</td>
<td>180</td>
</tr>
<tr>
<td>24.3 Test-case description</td>
<td>182</td>
</tr>
<tr>
<td>References</td>
<td>184</td>
</tr>
<tr>
<td>Test-case No</td>
<td>Description</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>25</td>
<td>Test-case No 28: The lock-exchange flow (N, PA)</td>
</tr>
<tr>
<td>25.1</td>
<td>Practical significance and interest of the test-case</td>
</tr>
<tr>
<td>25.2</td>
<td>Definitions and physical model description</td>
</tr>
<tr>
<td>25.3</td>
<td>Test-case description</td>
</tr>
<tr>
<td></td>
<td>References</td>
</tr>
<tr>
<td>26</td>
<td>Test-case No 29a: The velocity and shape of 2D long bubbles in inclined channels or in vertical tubes (PA, PN) Part I: in a stagnant liquid</td>
</tr>
<tr>
<td>26.1</td>
<td>Practical significance and interest of the test-case</td>
</tr>
<tr>
<td>26.2</td>
<td>Definitions and model description</td>
</tr>
<tr>
<td>26.3</td>
<td>Motion in horizontal channel</td>
</tr>
<tr>
<td>26.4</td>
<td>Motion in inclined channel</td>
</tr>
<tr>
<td>26.5</td>
<td>Motion in vertical channel and in tube</td>
</tr>
<tr>
<td>26.6</td>
<td>Acknowledgements</td>
</tr>
<tr>
<td></td>
<td>References</td>
</tr>
<tr>
<td>27</td>
<td>Test-case No 29b: The velocity and shape of 2D long bubbles in inclined channels or in vertical tubes (PA, PN) Part II: in a flowing liquid</td>
</tr>
<tr>
<td>27.1</td>
<td>Practical significance and interest of the test-case</td>
</tr>
<tr>
<td>27.2</td>
<td>Definitions and model description</td>
</tr>
<tr>
<td>27.3</td>
<td>Motion in horizontal and inclined channel</td>
</tr>
<tr>
<td>27.4</td>
<td>Motion in vertical channel and in tube</td>
</tr>
<tr>
<td>27.5</td>
<td>Acknowledgements</td>
</tr>
<tr>
<td></td>
<td>References</td>
</tr>
<tr>
<td>28</td>
<td>Test-case No 30: Unsteady cavitation in a Venturi type section (PN)</td>
</tr>
<tr>
<td>28.1</td>
<td>Practical significance and interest of the test-case</td>
</tr>
<tr>
<td>28.2</td>
<td>Definitions and physical model description</td>
</tr>
<tr>
<td>28.3</td>
<td>Geometry and boundary conditions</td>
</tr>
<tr>
<td>28.4</td>
<td>Comparison with experiments</td>
</tr>
<tr>
<td></td>
<td>References</td>
</tr>
<tr>
<td>29</td>
<td>Test-case No 31: Reorientation of a Free Liquid Interface in a Partly Filled Right Circular Cylinder upon Gravity Step Reduction (PE)</td>
</tr>
<tr>
<td>29.1</td>
<td>Practical significance and interest of the test-case</td>
</tr>
<tr>
<td>29.2</td>
<td>Definitions and model description</td>
</tr>
<tr>
<td>29.3</td>
<td>Experimental setup and procedure</td>
</tr>
<tr>
<td>29.4</td>
<td>Results</td>
</tr>
<tr>
<td>29.5</td>
<td>Proposed calculations</td>
</tr>
<tr>
<td></td>
<td>References</td>
</tr>
<tr>
<td>30</td>
<td>Test-case No 33: Propagation of solitary waves in constant depths over horizontal beds (PA, PN, PE)</td>
</tr>
<tr>
<td>30.1</td>
<td>Practical significance and interest of the test-case</td>
</tr>
<tr>
<td>30.2</td>
<td>Definitions and model description</td>
</tr>
<tr>
<td>30.3</td>
<td>A series of three test-cases</td>
</tr>
</tbody>
</table>
30.4 Summary of the required calculations for propagations of solitary waves
References ................................................................. 268

31 Test-case No 34: Two-dimensional sloshing in cavity - an exact solution (PA)
31.1 Practical significance and interest of the test-case ............................................. 269
31.2 Definitions and physical model description ......................................................... 270
31.3 Test-case description ......................................................................................... 273
References ............................................................................................................ 275

32 Test-case No 35: Flow rate limitation in open capillary channels (PE)
32.1 Practical significance and interest of the test case ............................................... 277
32.2 Definitions and model description ...................................................................... 278
32.3 The Experimental Test Case ............................................................................. 280
32.4 Results ............................................................................................................. 284
References ............................................................................................................ 290

33 Test-case No 36: Kelvin-Helmholtz instability (PA)
33.1 Practical significance and interest of the test-case ............................................... 291
33.2 Experiment description ..................................................................................... 292
33.3 Inviscid linear analysis ....................................................................................... 294
33.4 Experimental results to be predicted by the simulation .................................... 296
References ............................................................................................................ 298

Index ....................................................................................................................... 299
Foreword

I am very pleased to introduce to the Series what I believe will become a standard reference in multiphase flow in future years. Research in this area has increasingly been focussed on the prediction of the position and temporal movement of phasic interfaces, using the so-called interface tracking methods. The simplest example of this type of system is the rise of a single bubble in a stationary fluid. However, systems of ever-increasing complexity are being predicted and, as with all numerical methods, it is difficult to establish the accuracy and efficacy of the techniques being employed, particularly when there is a dearth of experimental data for validation.

One way of increasing confidence in predictions is to compare the methods used with standard "benchmark" examples. In this book, no less than 33 separate test cases are presented in sufficient detail to allow extensive testing of interface tracking methods. The Editors (Drs. Jamet, Lebaigue and Lemonnier) have drawn together an impressive team for this Herculean task and the outcome will, I am sure, be immensely influential in progressing this important activity.

G. F. Hewitt
Series Editor
Preface

Why collect test-cases for interface tracking methods?

Several years ago, Hewitt et al. (1986) suggested that refined modelling of two-phase flow was a major key in meeting some complex industrial challenges associated with nuclear energy production. In particular, they reported that the understanding of the intricate heat transfer and fluid mechanics phenomena that control the critical heat flux or the pressurized thermal shock could not be easily reached within the frame of area-averaged or time-averaged models. In addition, the understanding of the interaction of probes with two-phase flows or the local conditions controlling wall boiling could benefit from a refined analysis of two-phase flows describing both the motion of each phase and that of the interfaces.

Beyond the energy field, the oil industry is also facing new challenges related to two-phase production of oil and gas. Sizing pipelines, separators and predicting the hydrate formation requires a flow description at a scale which is not covered by the existing 1D area-averaged models. From these examples arising from nuclear engineering and the oil industry, there is clearly a definite need to refine the models scale of analysis of two-phase flow with or without phase change.

Modeling requires characterizing flow and heat transfer at a scale consistent with the scales described by the models. When refining the scales of observation, instrumentation may become unacceptably intrusive or mere observation may become impossible without hampering the flow features by modifying the boundary conditions. An example of this situation is forced convective boiling. Details of the high pressure water flows close to the walls are probably beyond the reach of existing experimental techniques for several years and refined modeling was identified as a possible breakthrough to progress towards an in-depth physical understanding (Delhaye & Garnier, 1999).

Another objective favouring the development and the use of local models of two-phase flows is the tremendous difficulty in providing appropriate models (closure relations) to local-time-averaged models. Solving at a refined scale and analyzing the results by averaging them at the scale relevant to the time-averaged model is a possible way to identify appropriate closure relations to these averaged models.

However, local modeling of two-phase flow must not be confused with simulation as it is for example understood when solving the Navier-Stokes equations for
single-phase flow. Indeed, wetting phenomena, coalescence physics or heat transfer along a moving contact line cannot be described and must be modeled. As a consequence and as usual when modeling is involved, validation is necessary to gain confidence in the model predictions.

A historical view

In 1994, CEA started studying new methods to describe local two-phase flows and heat transfer with phase change. At that time, several two-phase CFD modeling methods or computational multiphase flow dynamics models (CMFD) were developed, but the inclusion of phase change into them was still a real challenge. Among all tracks which were identified, two main paths were explored to account for phase change phenomena: improving front tracking algorithms to account for the normal velocity discontinuity at the interface, and modifying the thermodynamic description of the interface within a single fluid approach. It was readily demonstrated that various physical and numerical problems were to be solved and that the evaluation of the potential solutions required reference situations where both the physics and the numerical techniques were precisely controlled. This was the basic idea of the test-cases.

In France and in Europe, several groups were also interested in these problems and during two meetings on January and June 2000 in Grenoble, France, it was realized that the need for test-cases was merely universal in this community and that exchanging, or better sharing, a common set of well tried and tested benchmarks could benefit to the progress of CMFD development. A first set of nearly 20 test-cases were then decided. Originally written in French, it was thought useful to invite European colleagues to contribute and to select English as a common language. Next, collecting these test-cases into a book was the sound and logical follow-up of the basic idea to provide worldwide developers with this previously scattered information.

Multiphase Science and Technology traditionally fosters this type of activity. Hewitt et al. (1986) edited a selection of reference data sets for validating 1D area-averaged two-phase flow and later, Hewitt et al. (1991) provided a forum to discuss the merits of various systems codes based on their ability to describe the physical situations relative to the collected data. The editors of this book thank Multiphase Science and Technology for its constant help in suggesting contributors and organizing the internal review of the proposed test-cases.

Organization of the test-cases collection

Test-cases were initially collected rather randomly and as they became more and more numerous, it was deemed important to provide the reader with the primary interest of the test-case and the targeted part of the CMFD model. This is indicated by capital letters directly following the title of the test-case. Two main categories are proposed:
• **N**: Purely numerical test-case to check for example some discretization methods,

• **P**: Physical test-case to verify a selected physical model or phenomenon controlled by the balance of selected effects.

In this latter category, further subdivision was considered:

• **PN**: Physical test-case compared to a reference numerical method regarded as more accurate

• **PA**: Physical test-case compared to an analytical solution possibly evaluated numerically

• **PE**: Physical test-case compared to an experiment

• **PC**: Test of coherence

A tentative sorting may be proposed according to the type or number of competing physical mechanisms involved in the test-case.

• **Test with only one effect:**
  
  – Pure transport (numerical scheme only: rotation, translation, stretching, etc.)
  
  – Interface deformation in a prescribed velocity fields
  
  – Shock jump conditions

• **Two or three terms of the momentum balance equation:**
  
  – Surface tension truncation errors against viscosity (spurious currents)
  
  – Buoyancy against surface forces (Rayleigh-Taylor)
  
  – Inertia against surface tension forces (oscillation of an inclusion)
  
  – Inertia against viscous forces (capillary standing waves, solitary capillary wave)
  
  – Buoyancy against drag forces (rise of an inclusion)
  
  – Viscosity contrast (two-phase Poiseuille flow)
  
  – Compressibility contrast (shock-bubble interaction)

• **Phase-change:**
  
  – Heat conduction and mass balance (1D Stefan problem, plane or spherical symmetry)
  
  – Bubble growth in a superheated liquid

• **Solid surface effects:**
  
  – Contact angle (pinning)
  
  – Capillary rise upon gravity reduction
  
  – Droplet impact and bouncing on a hot wall
• Local mechanisms with more complex situations:
  – Drop impact on a liquid film
  – Gas bubble bursting at a free surface
  – Collision of two droplets (hydrodynamics)
  – Shape of long bubbles in a tube

• Complex mechanisms or situations:
  – Mould filling by a viscous jet (inertia, viscosity and gravity)
  – Phase inversion in a closed box (mass balance, with viscosity and surface tension)
  – 2D sloshing
  – Lock-exchange flow
  – Unsteady cavitation in a Venturi

Each test-case is self-supporting and focused. The interest and emphasis are developed in a first section. Next, the theory necessary to understand the physical situation and the reference model is shortly explained with a discussion of its validity domain. Necessary references are provided. Next, the details of the test-case are provided i.e. the definition of the computation domain, the boundary conditions and the physical properties. Finally some results in a form that allows an easy handling (analytical formula, arrays of figures) are proposed with a common method for evaluating the errors between the calculated results and the reference.

Finally to ensure each data set is complete, a referee has been selected within the group of contributors to play the role of a potential user of the test-case. When the input of this internal referee was deemed significant by the authors they usually included him as the last author of their test-case.

D. Jamet, O. Lebaigue, H. Lemonnier
CEA/Grenoble, France

References


Chapter 1

Test-case No 1: Rise of a spherical cap bubble in a stagnant liquid (PN)

Olivier Lebaigue, DER/SSTH/LMDL, CEA/Grenoble
38054 Grenoble Cedex 9, France
Phone: +33 (0)4 38 78 36 70, Fax: +33 (0)4 38 78 50 36
E-Mail: olivier.lebaigue@cea.fr

Christophe Duquennoy, EDF-SEPTEN, 12-14 av. Dutrievoz,
69628 Villeurbanne Cedex, France, E-Mail: christophe.duquennoy@edf.fr

Stéphane Vincent, TREFLE - UMR CNRS 8508, ENSCPB
Université Bordeaux 1, 33607 Pessac Cedex, France
Phone: +33 (0)5 40 00 27 07, Fax: +33 (0)5 40 00 66 68
E-Mail: vincent@enscpb.fr

Abstract

The test case concerns the simulation of a fluid inclusion rising in another stagnant fluid. The transient rise velocity, and the steady-state rise velocity and shape should be compared to the results obtained with an accurate numerical technique.

1.1 Practical significance and interest of the test-case

This test-case could usually be considered as a very preliminary one for a new numerical method. An extensive tester may want to reproduce most parts of the Clift, Grace and Weber map [Clift et al., 1978]. However, this selected case deserves special attention for the result not only consists in a final shape of the bubble (that is nevertheless a real criteria of comparison) but also in a precise build-up of the bubble velocity, starting from rest, exhibiting an overshoot before reaching its final asymptotic value.
To get the proper results, mainly the correct terminal velocity, and to reproduce
the overshoot, a numerical method has to take accurately into account buoyancy,
viscous stresses and surface tension effects. In particular, this test allows validating
the numerical model that takes care of jump conditions at the interface (see e.g. Scardovelli & Zaleski, 1999). However, the test is less severe than the "Free rise
of a liquid inclusion in a stagnant liquid", a test-case proposed by Lemonnier and
Hervieu, presented in this volume.

1.2 Definitions and model description

The situation of the test-case is relative to a fluid inclusion rising in another fluid.
The inclusion and the surrounding fluid are initially at rest. Gravity induced
buoyancy is the only force inducing the motion. The test-case consists in the
computation of the transient build-up of the velocity of the rising inclusion that
finally reaches a constant value.

The physical model is reduced to Navier-Stokes equation in both phases, a
constant surface tension at the interface. No phase-change takes place at the
interface. As the solution does not depend on a possible compressibility of one
or both of the phases, the test-case can be conducted in both cases (compressible
/ incompressible), depending on specific features of the numerical method to be
evaluated.

Reference calculations are available in non-dimensional units; however, a typical
set of dimensional physical parameter is suggested. The length scale of the problem
is the initial diameter \(d_e\) of the inclusion whose initial shape is spherical. The velocity
scale for the speed of displacement of the center of mass \(U\) is,

\[ U_c = \sqrt{gd_e}, \tag{1.1} \]

where \(g\) is the acceleration of the gravity. The time scale is therefore

\[ t_c = \frac{\sqrt{d_e}}{g}. \tag{1.2} \]

Reduced parameters are \(\tau = t/t_c\) and \(u = U/U_c\). According to these definitions, the
non-dimensional reference calculation consist in the reduced time evolution of the
speed of displacement of the center of mass:

\[ u = U/U_c = f(\tau) = f(t/t_c). \tag{1.3} \]

The computation can be conducted either for an axisymmetrical domain or in a
true three-dimensional domain. As the limited extend of the domain has an impact
on the terminal velocity of the inclusion (see e.g. Harmathy (1960)), the size of
the computational domain has to be increased as long as an effect on the results is
noted. As a rough first estimate, we suggest that that the computational domain
has a minimal extend equal to ten diameters in all directions. According to the
work of Harmathy (1960), the shape of the bubble is not affected by the domain
extension whereas the terminal rise velocity modification can be estimated through
Figure 1.2: Recirculation zone and steam lines at reduced time $\tau = 2.86$. After a figure of Benkenida (1999).

- As an example, we suggest the following physical properties: $\rho_L = 1000$ kg.m$^{-3}$, $\rho_V = 10$ kg.m$^{-3}$, $\mu_L = 0.273556$ Pa.s$^{-1}$, $\mu_V = 0.00273556$ Pa.s$^{-1}$, $\sigma = 0.1$ N.m, $g = 10$ kg.s$^{-2}$, $d_e = 0.02$ m.

- Extract the position of the center of mass of the inclusion and then deduce its speed of displacement. The first point of comparison is the value of the reduced asymptotic velocity. This value can be obtained even with a peculiar point of the interface, such as the apex. Of course, in this later case, the temporal evolution around the overshoot (Figure 1.1) cannot be captured.

- In addition to the main result, additional features consist in comparisons of the non-dimensional values of the over-shoot in the build-up of velocity (Figure 1.1).

- Further comparisons are the shape of lines of current, the equilibrium shape of the inclusion and the size of the recirculation zone (Figure 1.2). This late characteristic requires that the inclusion has risen a length of more than ten diameters (Hnat & Buckmaster, 1976).

References


