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The French experience of twenty-five years of co-operative research programs in the field of two-phase flows

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Abstract—Gas–liquid or liquid–vapour two-phase flows are encountered in many industrial systems and processes, such as nuclear reactors, cryogenic engines for space rockets, chemical engineering contactors, oil wells, pipelines and conventional components in use in the thermal industry (e.g. evaporators or condensers). Research and Development projects undertaken by French laboratories are reviewed and illustrated in this paper. Co-operative research programs on two-phase flows have been carried out in France for more than twenty-five years and have led to a network of French laboratories which are now internationally recognised. They have also made possible the transfer of technology resources from basic research to industrial applications. © Elsevier, Paris

two-phase flows / co-operative research programs / GREDIC / GRETh

Résumé — Vingt-cinq ans d'actions concertées françaises sur les écoulements diphasiques. Les écoulements diphasiques liquide–gaz ou liquide–vapeur se rencontrent dans de nombreux systèmes, allant des réacteurs nucléaires aux moteurs cryotechniques des lanceurs spatiaux, en passant par certains contacteurs du génie chimique, les puits et les conduites utilisés pour le transport et l'extraction des produits pétroliers et les composants classiques de la thermique industrielle, tels que les évaporateurs ou les condenseurs. On passe ici en revue les possibilités de recherche et de développement sur les écoulements diphasiques offertes par les laboratoires français à la suite d'une série d'actions concertées sur le plan national, qui ont contribué à placer ces laboratoires parmi les meilleurs au monde et à accroître de façon significative les transferts de connaissances entre la recherche de base et les applications industrielles. © Elsevier, Paris

écoulements diphasiques / actions concertées / GREDIC / GRETh

1. THE ORIGIN OF THE CO-OPERATIVE VENTURES

In the early 1970's, the main Research & Development effort on two-phase flows was essentially devoted to the nuclear domain, and focused on steam-water flows likely to be found in nuclear power plants and in naval propulsion or research reactors. However, the increasing number of complex problems, raised both from the theoretical and the applied standpoints, rapidly induced the management of the CEA and EDF to persuade the CNRS to initiate a Programmed Topical Action on two-phase flows in 1976. In parallel and since 1972, the DGRST (délégation générale à la Recherche scientifique et technique, General Delegation for Scientific and Technical Research), owing to the numerous industrial applications involving the complexity of two-phase flows, supported a major co-operative venture in the same field. These two lines of action enabled France not only to acquire relevant scientific and technical results, but, above all, to create research teams whose expertise is now internationally recognised, as witnessed in particular by the Third International Conference on Multiphase Flow (ICMF'98) organised by Professor J. Bataille, which took place in Lyon, June 8–12, 1998.

2. CO-OPERATIVE PROGRAM ON NON-NUCLEAR INDUSTRIAL TWO-PHASE FLOWS (1986–1990)

2.1. Evaluating the needs of industry

As early as 1979, the DGRST Mechanical Engineering Committee had financed an in-depth investigation

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into the scientific and technical deadlocks associated with fluid mechanics in five industrial sectors: waste water management, paper industries, food industry, hydraulic transmission and control systems, and chemical engineering. This investigation was entrusted to the Bertin Company, and was followed up by a group of experts from the Mechanical Engineering Committee. It allowed eight major priority research axes in fluid mechanics to be identified. Amongst these axes were filtration and rheology, which formed the subject of co-operative programs initiated in 1982 and 1984, respectively, as well as two-phase flows which generated many of the problems faced by certain industrial sectors, especially sectors such as waste water management, chemical engineering, and the energy sector (rational production and use of energy).

2.2. Implementing the co-operative program

From the Bertin Company and the CEA initiative, a co-operative program proposal concerning *non-nuclear industrial two-phase flows* was drafted in 1984 and submitted to various organisations likely to sponsor the project. Two objectives were clearly identified:

1) transferring the knowledge acquired in the nuclear sector towards the non-nuclear mechanical engineering and energy sectors;

2) acquiring new knowledge in response to the real-life concerns in the latter sector.

The co-operative program grouped, as partners, the CEA/Grenoble and the Bertin Company, as well as the following six CNRS laboratories:

- the Lyon Laboratory of Fluid Mechanics and Acoustics (Laboratoire de mécanique des fluides et d'acoustique, LMFA)
- the Nancy Laboratory of Theoretical and Applied Energy and Mechanics (Laboratoire d'énergétique et de mécanique théorique et appliquée, Lemta)
- the Toulouse Institute of Fluid Mechanics (Institut de mécanique des fluides de Toulouse, IMFT),
- the Grenoble Institute of Mechanics (Institut de mécanique, IMG)
- the Rouen Laboratory for Transport Phenomena in Reactive Media (Laboratoire de phénomènes de transport dans les milieux en réaction, LESP, Coria)
- the Paris Laboratory of Physics and Mechanics in Heterogeneous Media, (Laboratoire de physique et mécanique des milieux hétérogènes, ESPCI).

Sponsorship was extended over five budget years (1985–1989) and was provided by the Ministry of Research, AFME, CNRS, CEA, EDF, and the Bertin Company. The research work was divided into six topics:

- development and validity of two-phase pipe flow models (CEA/G),
- interfacial instability (CEA/G, Coria, Bertin),
- phase separation in singularities (CEA/G, IMFT, Lemta),
- multidimensional dispersed flows (ECL, IMFT, IMG, LESP, Bertin),
- transition between counter-current and co-current flows (CEA/G, Lemta),
- measurement methods (CEA/G, IMG, ESPCI).

The scientific and financial management of the co-operative program was undertaken by a research group, the GREDIC (Groupement pour la recherche sur les écoulements diphasiques en conduite, Research Group on Two-Phase Pipe Flows) involving the CEA and the CNRS from 1985 to 1987, and the CEA, the CNRS, EDF and the Bertin Company as of 1987.

2.3. Assessment of the co-operative program

An assessment symposium was held at the MRT in October 1990, during which the scientific and technical conclusions of the co-operative program were presented to a public of industrial firm managers. In the course of the symposium, a special session was devoted to French expertise and knowledge in the field of measurement techniques applicable to two-phase flows. This session was placed under the auspices of the Ministry of Research and the Société hydrotechnique de France, whose Two-Phase Flows section had initiated an investigation into the industrial needs and the expertise of French laboratories concerning two-phase flow instrumentation.

The scientific and technical achievements of this co-operative program are described in reference [1]. Amongst the significant results, one notes in particular:

- the importance of two-phase pipe flow model qualification, not only for the general characteristics of the flow (pressure drop, void fraction), but also for the characteristics of wave propagation phenomena (velocity, amplification, and damping);
- the discovery of two-phase flow structures in the intake pipings of ignition-controlled engines;
- the complete modelling of a swirl-type mechanical sprayer;
- the understanding of the flow structures in singularities such as sudden enlargements and tee-junctions;
- the development of refined modelling schemes for bubbly or droplet flows, taking into account the turbulence of the continuous phase and the interactions between this phase and the dispersed phase;
- the creation of a local database on dispersed flows in typical situations such as sudden enlargements, boundary layers, jets, tee-junctions;
- the implementation of computer codes for bubbly or droplet dispersed flows in complex geometries;

- the understanding of hydrodynamic processes leading to the transition between counter-current flow and co-current flow, in the case of a liquid film trickling down a vertical wall and subjected to a counter- current gas flow;

- the development and qualification of a measuring technique permitting the simultaneous determination of the void fraction, the interfacial area, and the size of the bubbles in a bubble column;

- the development and qualification of a grid velocimeter permitting the measurement of particle velocity in a dispersed flow;

- the feasibility of using nuclear magnetic resonance (NMR) for two- phase flow metering.

3. THE GREDIC, THE GDR 1027 RESEARCH GROUP OF THE CNRS (1992-1995)

On completion of the previous co-operative program and after many contacts with the industry, it appeared that numerous problems required the modelling of multidimensional two-phase flows and that an on-going effort should be devoted to developing measurement techniques for two-phase flows.

Therefore, at the request of the co-operative program follow-up committee and the GREDIC's management committee, the creation of a research group (GDR) called Ecoulements diphasiques: modélisation multidimensionnelle et techniques de mesure (Two-phase flows: multidimensional modelling and measurement techniques) was proposed to the CNRS.

3.1. The partners

Created on the 1st January 1992, the CNRS's GDR 1027 kept its GREDIC designation and grouped in a very close partnership the following working teams of the CNRS, the CEA, EDF and the Bertin company.

3.1.1. CNRS (Engineering Sciences Department, 'Département Sciences pour l'ingénieur')

- the Lyon Laboratory of Fluid Mechanics and Acoustics (Laboratoire de mécanique des fluides et d'acoustique, LMFA);

- the Nancy Laboratory of Theoretical and Applied Energy and Mechanics (Laboratoire d'énergétique et de mécanique théorique et appliquée, Lemta);

- the Toulouse Institute of Fluid Mechanics (Institut de mécanique des fluides de Toulouse, IMFT);

- the Grenoble Laboratory of Geophysical and Industrial Flows (Laboratoire des écoulements géophysiques et industriels, LEGI);

- the Rouen Laboratory for Transport Phenomena in Reactive Media (Laboratoire de phénomènes de transport dans les milieux en réaction, LESP, Coria);

- the Paris Laboratory of Physics and Mechanics in Heterogeneous Media (Laboratoire de physique et mécanique des milieux hétérogènes, ESPCI).

3.1.2. EDF (Research and Development Directorate, Direction des études et recherches)

- the Department of Heat Transfer and Aerodynamics (département «Transferts thermiques et aérodynamiques», TTA);

- the National Laboratory of Hydraulics (Laboratoire national d'hydraulique, LNH).

3.1.3. CEA (Nuclear Reactor Directorate, Direction des réacteurs nucléaires)

- the Thermal-Hydraulics Laboratories for Industrial Applications of CEA/Grenoble (Service de thermohydraulique pour les applications industrielles).

3.1.4. Bertin & Co.

- Fluid Mechanics Division.

3.2. Research themes

From 1992 to 1995, the GREDIC activities were divided according to two themes: multidimensional modelling of dispersed flows, and measurement methods adapted to gas–liquid two-phase flows.

The *Multidimensional Modelling* theme involved seven lines of action: (1) wall and interfacial transfers in bubbly flows, application to two-phase mixing; (2) bubbly multidimensional turbulent flows; (3) modelling of dense dispersed flows; (4) modelling of atomisers; (5) two-phase flows in rotation; (6) numerical behaviour of two-phase flow multidimensional models; (7) modelling of multidimensional dispersed flows.

The *Measurement Method* theme involved five lines of action: (8) tomographic methods in two-phase flows; (9) light diffusion in two-phase flows; (10) characterisation of a liquid–liquid dispersion against coalescence; (11) qualification of an NMR method with a view to determining volume fractions and flow rates of the phases in a two-phase flow; (12) development of local measurement methods for two-phase flows.

3.3. The GREDIC operating scheme

During these four years, the GREDIC partners met regularly either within the scope of GREDIC-specific meetings, or at various scientific events (French and international conferences, thesis defences, scientific committees of laboratories, etc.). They also took an active part in two other CNRS research groups (microgravity and numerical fluid mechanics).

Annual meetings were held in Grenoble (6–7 April 1993) and Toulouse (30–31 April 1994). Furthermore, a GREDIC presentation meeting took place in Grenoble on 27 January 1995, with forty-five attendants, one-half of whom were industrial managers. Finally, an assessment symposium on the scientific results of the GREDIC was held in Paris on 23 June 1995. The presented papers formed the subject of a special issue of *La Houille Blanche* [2]. Acknowledging GREDIC's impact in the field of fluid mechanics, the Société hydrotechnique de France sponsored the previous two meetings.

In the course of its four operating years, 1992 to 1995, the GREDIC was financially supported by the CNRS, the CEA, EDF, the Ministry of Research and the Bertin Company.

3.4. The results

The GREDIC scientific work during the years 1992–1995 was particularly productive, as shown in the articles published in reference [2] as well as the number of theses either already defended or still in progress at the GREDIC's partner laboratories. Also notable are the significance of the contracts obtained by the partners with various organisations or industrial firms, and the international relations developed through networks and through attendance at scientific events.

The GREDIC partners took a very active part in two international conferences:

– third International Workshop on Two-Phase Flow Fundamentals, London, 1992;

– second International Conference on Multiphase Flow, Kyoto, 1995.

Furthermore, the international acknowledgement of French research on two-phase flows and the dynamics of the teams involved, allowed France to be chosen as the organising country for the 'Third International Conference on Multiphase Flow' (ICMF '98). This took take place in Lyon, 8–12 June 1998, under the chairmanship of Professor J. Bataille.

4. THE GREDIC, THE GDR 1205 RESEARCH GROUP OF THE CNRS (1996–1999)

A close and productive relationship between the GREDIC partners, on-going and active contacts with foreign laboratories, as well as the rise of basic problems derived from industrial problems, led the CNRS to extend the activities of the GDR 1027. The new group, GDR 1205, called *Instabilités et turbulence dans les écoulements diphasiques* (Instabilities and turbulence in two-phase flows) kept the GREDIC designation, but differentiated itself from the previous group as follows:

initiation of new activities concerning interface dynamics;

interruption of activities concerned with measurement methods, which were taken up by other entities;

addition of two new teams: the LIMSI (Orsay) and the Laboratory of Modelling Techniques in mechanics (Laboratoire de modélisation en mécanique, Paris).

Research themes

The entire program includes 20 lines of action, broken down into two themes: interface dynamics and dispersed flows. The global program is a major contributor to the comprehension of instability and turbulence phenomena in two-phase flows. The 20 current activities are listed in the *table* below, including the title, the laboratory, and the scientific manager for each activity. Reference [3] contains a detailed description of each one of the 20 ventures. The GREDIC activities from January to 30 June 1997 are described by lines of action in reference [4].

Although the *Measurement method* theme is no longer explicitly included in the current GREDIC's program, the GREDIC partners took a very active part in the specialists' meeting concerning measurement methods for two-phase flows, which was organised by the OECD in Santa Barbara from the 17th to the 20th of March 1997. Six invited papers by GREDIC partners were presented at this meeting.

5. A RESEARCH GROUP ON HEAT EXCHANGERS: THE GRETH (GROUPEMENT POUR LA RECHERCHE SUR LES ÉCHANGEURS THERMIQUES)

The improvement of industrial technologies in the direction of enhanced efficiency and cleanliness is a major stake for our economy. All elements such as heat exchangers and other thermal equipment (boilers, furnaces, incinerators, condensers, etc.) are essential in any energy control and environment protection policy. These equipment items are in use both in industrial processes (chemical industries, oil industries, steel industries, food industries...) and in transport (cars, aeronautics) and housing (heating and air conditioning...).

	INTERFACE DYNAMICS		
1	Atomisation mechanisms. Experimental study and modelling.	CORIA, Rouen	M. Ledoux
2	Liquid film destabilisation by gravity or centrifugal effects.	LPMMH, Paris	L. Lima
3	Instabilities in liquid films sheared by a gas phase.	IMFT, Toulouse	F. Charru
4	Stability of liquid films in ducts with interfacial interaction at the interface.	LEMTA, Nancy	B. Izrar
5	Magnetic field control of interface stability in a rotating reference system.	LEMTA, Nancy	M. Souhar
6	Instability study of a horizontal liquid–vapour interface for film boiling control.	LIMSI, Orsay	P. Le Quéré
7	Application of the continuous description of a liquid-vapour interface to the dynamics of two-phase systems with phase change.	CEA, Grenoble	O. Lebaigue
8	Characterisation of gas–liquid two-phase flow pattern changes: development and implementation of advanced signal processing methods.	CEA, Grenoble	E. Hervieu
9	Characterisation of complex dynamic systems.	LESP, Rouen	G. Gouesbet
10	Structure of upward vertical intermittent flow.	IMFT, Toulouse	J. Fabre
	DISPERSED FLOWS		
11	Gravity-controlled bubbly flow	LMFA, Lyons	M. Lance
12	Macro-simulation of bubbly gas-liquid flows.	LMFA, Lyons	M. Lance
13	Large eddy simulation of dispersed turbulent two-phase flows.	IMFT, Toulouse	J. Magnaudet
14	Development and validation of an Eulerian model of turbulent two-phase flows with dispersed inclusions.	LNH, Charou	O. Simonin
15	Dynamics of particle clouds.	LESP, Rouen	A. Berlemont
16	Pseudo-turbulence in dispersed flows.	LEGI, Grenoble	A. Cartellier
17	Pseudo-turbulence in dispersed two-phase media.	LMM, Paris	D. Lhuillier
18	Refined modelling of heat and mass transfer in boiling steam–water flows.	TTA, Chatou	E. Brière
19	Multidimensional modelling in dense two-phase media.	Bertin, Plaisir	E. Znaty
20	Instabilities and turbulence in two-phase flows.	IMFT, Toulouse	C. Suzanne

Owing to the diversity and spread of the industrial network involved, it was deemed important to organise target-oriented research and to promote innovation in industrial firms, particularly the small-and medium-sized companies and industries, by transferring the acquired knowledge to them. In 1984, in order to meet these objectives, the CEA and Ademe (Agence pour l'environnement et la maîtrise de l'energie, Environment and Energy Control Agency) created a research group on heat exchangers, the GRETh (Groupement pour la Recherche sur les Échangeurs Thermiques), whose mission is to assist industrial firms in industrial thermal engineering. The group deals with the engineering offices, the users and consulting firms, the large and small firms, the thermal equipment manufacturers, etc. It currently numbers about a hundred members. The GRETh is located in the CEA centre of Grenoble.

The GRETh as a technological resource centre

The main three objectives of the GRETh are:

– to improve the basic knowledge of heat transfer equipment;

– to develop new product designs featuring higher performance and lower costs;

– to develop numerical simulation programs and databases.

This research group is more particularly devoted to *heat transfer in two-phase flows with evaporation and condensation*, high temperature heat exchangers, high performance applications of electricity, and clean, low-cost technologies (air cleaning equipment, processing of volatile organic compounds, waste valorisation and treatment, use of environment friendly cooling fluids...).

In addition to its own research capacity, the GRETh uses the expertise of researchers from the thermal hydraulics pole of Grenoble: CEA Département de thermohydraulique et de physique (Department of Thermal-Hydraulics and Physics), Joseph-Fourier University, Institut national polytechnique de Grenoble (Grenoble National Polytechnic Institute) with which it carries out the basic research work which could not be undertaken by the industrial firms, and particularly the small-, and medium-sized businesses. It also relies on the CNRS (Ecodev program) for basic research projects.

Large public organisations (CEA, EDF, Ademe, European Union) contribute 70 % of the GRETh budget, the balance being supported by the industrial members.

Furthermore, certain industrial technical centres are associated with the GRETh studies, such as the Cetiat (Centre technique des industries aérauliques et thermiques, Technical Centre for Aeraulic and Thermal Industries) and the Cetim (Centre technique des industries de la mécanique, Technical Centre for Mechanical Industries) which, like the CEA and Ademe, are founding members of the 'Club GRETh', a non-profit corporation under the French Act of 1901, grouping together the industrial members of the GRETh.

6. CONCLUSION

The activities conducted in the field of two-phase flows for more than twenty-five years enabled France to develop high competence teams, entrusted with target-oriented basic research on two-phase flows and in charge of transferring the results to the industrial sector. This effort must be followed up in order to help extend the innovation-friendly trends within French firms.

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