Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
International Journal of Thermal Sciences 45 (2006) 205–208
International Journal of Thermal Sciences
www.elsevier.com/locate/ijts

Review

Joint research program “Thermo- and Fluiddynamics in Boiling” Objectives of the program and cooperation of the partners

Dieter Gorenflo *

Thermodynamik und Energietechnik, Universitaet Paderborn, Warburger Strasse 100, D-33098 Paderborn, Germany

Available online 21 September 2005

Abstract

The objectives of the program and the method of approaching the problems are outlined. The projects of the program are listed and their theme-oriented interrelation is described. The various lines of cooperation between the partners, as one of the essential features of the program are discussed next. Finally, presentation of results on conferences during the past years is reported.

1. Objectives of the program and method of approach

So far, no general theory of nucleate boiling heat transfer has been developed. It should be based on the heat and mass transfer phenomena connected with vapour production in the superheated liquid layer in contact with the heated surfaces in evaporators. The most important part of these phenomena occurs within a distance of a few microns or less from the heated surface, when cavities in the micro structure of the surface are activated to produce vapour. Activation means that the superheated liquid in the cavities evaporates through the curved vapour–liquid interface of tiny bubble nuclei existing within the cavities. The nuclei will grow and release the vapour either in the form of spherical bubbles not much bigger than the cavities, particularly at high reduced saturation pressure $p^* = p_s/p_c$ (p_c = pressure at the critical state of the boiling liquid), or in the form of more or less irregularly shaped bubbles or vapour patches of much greater dimensions, depending on heat flux q and reduced pressure p^*.

It is obvious that direct experimental investigation of the phase-change processes inside the cavities is difficult to realize, because optical methods are influenced by the temperature gradient within the superheated liquid boundary layer, and probe techniques have to be adapted to the micro size of the cavities to produce reliable results.

Furthermore vapour production is characterised partly by mechanistic and partly by stochastic processes: By *mechanistic processes* because of the temporal sequence of events at each active nucleation site, with

(a) vapour leaving the heated surface,
(b) liquid approximately saturated being sucked in and becoming superheated, and
(c) vapour being produced and replacing the superheated liquid

by *stochastic and mechanistic processes* because of the *spatial distribution* of active sites on the surface and the *start* of activation at each individual site. Depending on the kind of the roughness structure the processes may lie somewhere between the extremes of a very regular and a highly irregular pattern.

A regular pattern will occur, if there exist enough, but not too many cavities on the surface, which are better apt to trap vapour nuclei than their neighbouring cavities, so that always the better apt cavities will be active and form ‘stable’ nucleation sites. On the other hand, a highly irregular pattern will prevail, if a sufficient number of cavities of the same size and shape exist close together. They will then act as *potential* active sites at a given, constant superheat ΔT of the wall. An inherent feature of nucleate boiling heat transfer is, however, that ΔT will be constant only on *average*. On a local scale instead, fast temperature fluctuations occur, because at the moment of vapour release from an active site, the remaining liquid and surrounding wall are cooled down when providing the necessary enthalpy of vapor-

* Tel.: +49 5251 60 2393; fax: +49 5251 60 3522.
E-mail address: digo@thet.upb.de (D. Gorenflo).

1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2005.08.009

ization. Then neighbouring similar cavities having accumulated their superheat in the meantime will become active, and the process of activation switches from place to place.

This situation in mind, it becomes obvious that a coherent threefold information, namely about heat transfer, vapour formation and microstructure of the heated surface is a prerequisite for the development of theoretically based prediction methods of nucleate boiling heat transfer. Therefore, this threefold approach was the objective of the experimental and the modelling parts of the joint research program.

2. Projects and theme-oriented interrelation

2.1. Selection of the projects

The individual projects combined in the joint research program are listed in Table 1. The projects were selected from 24 proposals that had been made early in 1996 by the various groups working on boiling heat transfer research in Germany at that time.

During several round table discussions on the actual research needs in boiling heat transfer, which were organized by the German Research Foundation (DFG) together with the Thermodynamics and Heat Transfer Section of Paderborn University, 12 projects had been pre-selected and then elaborated in detail to form a coherent research program. At the end of 1997, the final reduction was done by the referees of DFG, mainly under the aspect of having best synergy effects between the projects that would remain after achieving accordance with the upper limit of annual funds available for the whole program.

Work on most of the projects started during spring/summer of 1998. Additional funds for two projects, 3a and 3b, were granted two years later and were mainly dedicated to provide two expensive research tools useful for the whole group: a high-speed digital video-system with high local resolution and a system to determine the wetting characteristics of the test fluids under the same temperature/pressure conditions as in the heat transfer experiments of the other projects.

2.2. Links between the projects

The following requirements had to be met by the experiments providing data for the model developing groups:

Table 1
Survey of the projects

#	Leading scientist	University town, start of project	Theme	Heating element	Test fluid	Pressure p_s/bar or p_s/p_c
1	Erich Hahne	Stuttgart 07/98	Heat transfer and nucleation in pool-boiling: Influence of the thermal properties of the heated wall	horizontal tube, 15∅, Cu + SS[a], Au-plated	R134a, Iso-Propanol	p_s/p_c: 0.05–0.7
2	Dieter Gorenflo	Paderborn 04/98[b]	Heat transfer and bubble formation in pool boiling: Effect of basic surface modifications for heat transfer enhancement	horizontal tube, 1”∅, Cu + Cu/Ni10	R134a, Iso-Propanol	p_s/p_c: 0.02–0.8
3	Dieter Gorenflo, Andrea Luke	Paderborn 04/98[b]	Improvement of preparation, measurement and analysis of the micro structure of evaporator surfaces	see # 1, 2, 5, 6	see # 1, 2, 5, 6	
3a	Dieter Gorenflo	Paderborn 05/00[c]	Improvement of high speed video recording and analysis of bubble formation on evaporator surfaces	see # 1, 2, 6	see # 1, 2, 6	p_s/p_c: 0.02–0.8
3b	Andrea Luke	Paderborn 10/01[c]	Wetting behaviour and surface energy of evaporator surfaces	see # 1, 2, 6	see # 1, 2, 6	p_s/p_c: 0.02–0.8
4	Hans Burkhardt	Freiburg 06/99	Template based bubble identification and tracking in high speed image sequences	see # 1, 2, 6	see # 1, 2, 6	
5	Thomas Sattelmayer	München 03/98	Convection effects on bubble and boundary layer behaviour in subcooled flow boiling	horizontal plate, Cu, 60 × 40 × 500	H_2O	p_s: 0.25–4 bar
6	Hein Auracher	Berlin 04/98	Study of local heat transfer mechanisms along the entire boiling curve by means of microsensors	horizontal plate, Cu 19 + 35∅	Iso-Propanol (H_2O) (FC 3284)	p_s: 0.2–6 bar
7	Wolfgang Marquardt	Aachen 08/98	Identification and modeling of unifying heat transfer mechanisms along the entire boiling curve	see # 1, 2, 6	see # 1, 2, 6	
8	Karl Stephan	Stuttgart 01/99	Numerical simulation of heat transfer during growth of single vapor bubbles in nucleate boiling	see # 1, 2, 6	see # 1, 2, 6	

[a] SS—stainless steel.
[b] Still running.
[c] Measuring equipment.

(a) Shape and surface roughness of the heating elements should be of technical relevance;
(b) An extended range of saturation pressures should be investigated;
(c) Data on heat transfer, vapour formation and microstructure of the heated surface should be gathered in the same experiment;
(d) Local resolution of the measurements should be as high as possible.

Two additional measures were taken to produce coherent results:

(e) It was agreed to use reference fluids—refrigerant R134a ($CH_2F{\cdot}CF_3$) and 2-Propanol ($CH_3{\cdot}CHOH{\cdot}CH_3$)—obtained from a manufacturer by one of the partners and distributed to all others to guarantee in all experiments the same purity, as high as possible. Within the experimental temperature range of the test facilities used in projects 1 and 2, measurements could be done over a wide range of reduced saturation pressures p^* with these fluids (see Table 1), with extreme differences in the departure diameters of bubbles and also in the fluid motion induced by departing bubbles near the vapour–liquid interphase on the heated wall.
The low reduced pressures available in the case of 2-Propanol correspond to near-atmospheric pressures for water. Therefore, after first experiments with water further experiments were done with 2-Propanol also in project 6, thus avoiding the otherwise inevitable time-dependent modification of the heated surface caused by water when boiling at high heat fluxes. This aspect was less important in project 5, because its main objective was the development of new measuring techniques for the motion of the vapour/liquid interphase in subcooled flow boiling.
(f) The surface roughness of the heating elements used in projects 1, 2, 5 and 6 was produced always in the same way within project 3—either by grinding or sandblasting—and was then analyzed in this service project to permit a reliable comparison of the data.

Projects 1 and 2 were closely linked. In both, the heating element was a horizontal tube of approximately the same diameter. The entire experimental equipment and test procedure fulfilled the requirements of the so-called Standard-Apparatus for pool boiling heat transfer measurements. The same fluids were used in both projects and experiments were performed within approximately the same (wide) range of reduced pressures p^*. In both projects, the influence of the heating wall on heat transfer was studied, exploring the influences of wetting characteristics separate from those of material properties in project 1, whereas the main objective of project 2 was the separation of convective from evaporative influences on heat transfer caused by macro and micro structures of the surface.

The two central service projects 3 and 4 aimed at improving our comparatively poor knowledge on the microstructure of the heated surfaces and on the micro events of vapour formation. This will lead to a better understanding of the mechanism of heat transfer and better prediction methods. The same holds for the two additional projects 3a and b.

Projects 5 and 6 aimed at developing advanced measuring techniques for two-phase vapour/liquid systems. In project 5, optical methods for two-phase flow were improved to identify nucleate and convective contributions to heat transfer in subcooled flow boiling. Micro-probe and micro-thermocouple techniques developed in project 6 permitted a sensitive resolution of local and temporal temperature and wetting fluctuations in the immediate vicinity of the heated surface. In addition the results with water of project 5 provided new data for heat transfer in power plants, while the results of project 6 with organics serve as a basis to develop generalized prediction methods for different fluids.

On the modelling side, two approaches were chosen and pursued in parallel: In project 8 the region of *low heat fluxes*, when interaction between single bubbles is negligible, was studied, modelling the micro and macro regions around a bubble with special emphasis on fluid flow inside and outside a growing bubble and its influence on heat transfer. In project 7 the region of *high heat fluxes* with a two-phase vapour/liquid boundary layer near the heated wall was studied with the liquid–vapour interface of the wetting structure as key mechanism for heat removal due to evaporation along the entire boiling curve.

3. Cooperation of the partners

Close cooperation between the partners was one of the essential features of the joint program right from the beginning on. It mainly consisted in service contributions of the central projects 3 and 4 to all other projects, in regular meetings of the leading scientists and the PhD students involved in the projects, and in bilateral cooperation between partners.

The *service contribution* of preparing, measuring and analyzing the roughness structures of all heating elements, which was provided by Andrea Luke throughout the program, was one of the indispensable links between the projects, as outlined above. The same holds for identification and tracking of bubbles in high-speed image sequences developed in project 4. Unfortunately, the start of this project was delayed and results could be used by the partners only in a late stage of the program. As first applications indicate, bubbles sliding upwards along the heated surface of horizontal evaporator tubes may grow as fast as at the active site before detaching. It seems that this effect still needs to be considered more closely in advanced prediction methods.

Regular meetings of the leading scientists and the PhD students were organized within short time intervals to coordinate the service contributions, and discuss results and future activities. In addition, the PhD students met for 7 *workshops* at their universities under guidance of Andrea Luke to discuss work in progress and problems encountered. New measuring and computing techniques were the subjects of frequent supplementary meetings of some of the PhD students.

A very *close cooperation* existed between projects 6 and 7. The experimental part, i.e. the development of the micro-probe techniques and measurement of fluctuations of the two-phase boundary layer and the wall temperature was concentrated in

Table 2
Joint presentations of results on international conferences

#	Date	Place	Conference	Results of projects[a]
1	09/2000	Heidelberg, Germany	3rd European Thermal-Sciences Conference	1, 2, 3, 5, 6, 8
2	10/2001	Paderborn, Germany	IIR Conference on "Thermophysical Properties and Transfer Processes of New Refrigerants"	1, 2, 3, 3a, 4, 5, 6, 7, 8
3	08/2002	Grenoble, France	12th International Heat Transfer Conference	1, 2, 3, 3a, 8
4	05/2003	Montego Bay, Jamaica	5th International Conference on Boiling Heat Transfer	1, 2, 3, 3a, 5, 6, 7

[a] Project numbers according to Table 1.

Berlin, project 6, and simulations, modelling and identification of heat transfer mechanisms in Aachen, project 7.

4. Presentation of results

Coordinating publication of work in progress was another objective of the regular meetings. Joint presentation of projects was preferred, see Table 2, making the program known in the heat transfer community, as soon as the first results were available. In a conference at Paderborn University in 2001 attended by the referees of DFG and more than 120 participants from all over the world, all projects and the results obtained until that time were presented and discussed. The same holds for the International Conference on Boiling Heat Transfer (ICBHT) in 2003, where experts of boiling heat transfer come together every three years.

In addition, results of some projects were presented on other international conferences, such as EUROTHERM Seminars or the 4th ICBHT in 2000, and on national conferences, like the 8th National UK Heat Transfer Conference in 2003, annual meetings of DKV (the German Assoc. of Refrigeration and Air Conditioning) and of the Heat & Mass Transfer Section of VDI. For more information, see the reference lists of the articles below.

It is not the intention of this review to go into the results of the individual projects more in detail; this is also left to the articles below. In some cases, not all the goals have been reached, because it turned out that much more preliminary and fundamental work concerning the process of vapour formation and analysis of the roughness structure of the heating elements had to be done than originally anticipated, before coming to the main goal of the projects. For this reason some projects are still being continued, cf. Table 1. Nevertheless, it is felt that valuable new insights in the nature of boiling heat transfer have been gained, particularly on the interrelation between micro structure of the heating surface, vapour formation and the mechanism of heat transfer.

Acknowledgements

The partners of the joint research program gratefully acknowledge financial support by DFG. Thanks are due to the useful expert advice of the DFG-referees. The partners are also grateful to Erich Hahne for offering facilities for the many meetings of the leading scientists and PhD students in his institute, to Fa. Solvay Deutschland GmbH for supplying the refrigerant, and last but not least to Andreas Beutler from Wieland Werke AG, Ulm, for valuable support to project 2.