UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

August 13, 2002

MEMORANDUM TO: G. Wallis, Chairman, Thermal-Hydraulic
Phenomena Subcommittee

FROM: Paul Boehnert, Senior Staff Engineer
Technical Support Staff

SUBJECT: CERTIFICATION OF THE MINUTES OF THE ACRS SUBCOMMITTEE MEETING ON THERMAL-HYDRAULIC PHENOMENA, JULY 17,, 2002 - ROCKVILLE, MARYLAND

I hereby certify that, to the best of my knowledge and belief, the Minutes of the subject meeting issued August 13, 2002, are an accurate record of the proceedings for that meeting.

G. Wallis, Chairman

9/9/02

Date

UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D.C. 20555-0001

August 13, 2002

MEMORANDUM FOR: G. Wallis, Chairman, Thermal-Hydraulic Phenomena Subcommittee

FROM: P. Boehnert, Senior Staff Engineer

SUBJECT: MINUTES OF THE ACRS THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING, JULY 17, 2002 - ROCKVILLE, MARYLAND

A Working Copy of the subject meeting minutes is attached. I would appreciate your review and corrections as soon as possible. Copies are being sent to all ACRS members and to the Subcommittee Consultants for their information.

Attachment: As Stated

cc:
- ACRS Members
- S. Banerjee
- F. Moody
- V. Schrock
- R. Savio

cc via E-Mail:
- ACRS Members
- S. Banerjee
- F. Moody
- V. Schrock
- J. Larkins
- S. Bahadur
- R. Savio
- H. Larson
- S. Duraiswamy
- ACRS Staff Engineers

DRAFT COPY - PREPARED FOR INTERNAL COMMITTEE USE

CERTIFIED BY: G. wallis
9/9/02

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
THERMAL HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING MINUTES
DRAFT REGULATORY GUIDE ON CODE DOCUMENTATION - DG-1120 / RES T/H RESEARCH PROGRAM ON SUBCOOLED FLOW BOILING PHENOMENA

JULY 17, 2002
ROCKVILLE, MARYLAND

INTRODUCTION:

The ACRS Subcommittee on Thermal-Hydraulic Phenomena held a meeting on July 17, 2002 with representatives of the NRC Staff and its contractors. The purpose of this meeting was to: (1) continue review of the NRC Office of Nuclear Regulatory Research (RES) draft Regulatory Guide, DG-1120, "Transient and Accident Analysis Methods", and associated NRC Standard Review Plan Section 15.0.2, and (2) review the RES thermal-hydraulic research Program dealing with subcooled flow boiling phenomena. The entire meeting was open to the public. Mr. P. Boehnert was the cognizant ACRS staff engineer and Designated Federal Official (DFO) for this meeting. The meeting was convened by the Chairman at 8:30 a.m, June 26, 2002, and adjourned at 5:58 p.m. that day.

ATTENDEES

ACRS Members/Staff:		NRC Staff	
G. Wallis, Chairman	S. Banerjee, Consultant	J. Rosenthal, RES	S. Bajorek, RES
T. Kress, Member	F. Moody, Consultant	J. Staudenmeier, RES	
V. Ransom, Member	V. Schrock, Consultant	"V. J." Dhir, UCLA (RES Consultant)	
P. Boehnert, DFO		R. Caruso, NRR	

A list of public attendees is attached to the Office Copy of these Minutes.

The presentation slides and handouts used during the this meeting are attached to the Office Copy of these Minutes. The presentations to the Subcommittee are summarized below.

INTRODUCTORY REMARKS

Dr. Wallis convened the meeting. He noted that work on DG-1120 has been ongoing for over four years and he is happy to see that it is reaching a conclusion with the expected publication of the regulatory guide for public comment.

NRC OFFICE OF NUCLEAR REGULATORY RESEARCH PRESENTATIONS

Draft Regulatory Guide, DG-1120, "Transient and Accident Analysis Methods

The following topics were discussed regarding the subject draft regulatory guide:

- Background and Need
- Contents of DG-1096
- Response to Public Comments
- New Content in DG-1120
- Status and Summary

The NRC staff had developed a draft Regulatory Guide (DG-1096) and Standard Review Plan Section (SRP 15.0.2) to document a set of general principles applicable to the staff's review of all analytical computer codes. This effort was driven primarily by problems identified by the NRC staff (e.g., Maine Yankee Lessons Learned Report) and the ACRS (review of the AP600 passive plant design). The Guide described an acceptable Evaluation Model Development and Assessment Process (EMDAP) based on the Code Scaling, Applicability, and Uncertainty (CSAU) methodology. DG-1096 was reviewed by the ACRS in December 1998 and subsequently issued for public comment.

Following public comment, NRC held a Workshop where industry representatives expressed some concerns with DG-1096. NRC revised the guide in response to these concerns; the new guide has been renumbered as DG-1120. Significant revisions made include: addition of a graded approach to applying the EMDAP to changes to existing evaluation models (EMs), based on the significance of the proposed changes, and that the guide will not be applied to EMs for which no changes are proposed.

NRR will not reissue SRP 15.0.2 for public comment, as only minor changes were made in the initial version.

Subcommittee Comments on the above presentations included:

- In response to Dr. Banerjee, RES said that the guide will apply to all analyzed events, with a few exceptions (e.g., deign-basis accidents, severe accidents).

- In response to Messrs. Schrock and Wallis, Mr. Lauben, RES, noted that one of the drivers for development of this guide was the lack of adequate code documentation, as seen at Maine Yankee and during the AP600 design certification review.

- Dr. Ransom said that his concern is with the lack of adequate assessment for the codes. He noted that in many cases code assessment is a matter of judgment. Mr. Lauben said that the guide provides some direction regarding assessment, although more is incorporated by reference. Dr. Wallis said that a more quantitative approach is needed regarding both the performance of code assessment and to address the issue of determination of uncertainties.

- Dr. Ransom said that RES should reference the success criteria applicable to the CSAU requirements.

- Regarding the criteria cited for the EMDAP graded approach, Dr. Wallis said that the relevant sections of the Guide dealing with the criteria "Degree of Conservatism" and "Risk Significance of the Event" should be revised as they appear to be too vague.

- In response to Professor Schrock, RES said that vendors will be required to quantify the degree of conservatism existing in their models.

- Dr. Ransom said that the issue of "user effect" needs to be addressed. Mr. Caruso said that for LOCA analyses this is not a significant issue, as the codes allow few options. For other analyses, NRR indicated that this is an issue of concern, particularly for the reactor licensees.

- Professor Schrock expressed dissatisfaction with the Regulatory Guide in its current form, as it does not prevent the use of codes and code models that are clearly deficient.

- As a result of extended discussion, Messrs. Schrock and Wallis advised NRR that the so-called Graded Review Approach would apply only to a small class of code changes that are minor in nature. Professor Schrock said that the Regulatory Guide should make a clear delineation between LOCA calculations and other analysis cases

Subcommittee Caucus

The Subcommittee agreed that this matter should be reviewed by the full Committee during its September Meeting. Dr. Wallis requested that the Consultants provide written comment on this matter. He noted that he would provide some comments in writing as well. He indicated that Section 5 of the Reg. Guide ("Graded Approach for Applying the EMDAP Process") should be revised, particularly Sections 5.3 and 5.4.

SUBCOOLED BOILING EXPERIMENTAL PROGRAM IN SUPPORT OF TRAC-M MODEL IMPROVEMENT

Drs. S. Bajorek (RES) and "V. J." Dhir (UCLA - RES Contractor) discussed, in detail, the subject experimental program. Dr. Bajorek noted that modeling of subcooled boiling in two-fluid codes makes use of "heat-flux splitting". This leads to less-than-desirable results, such as the problems encountered by NRC in modeling certain accident events during the AP600 design certification review. The current subcooled boiling model in TRAC-M has similar shortcomings. The UCLA experimental program is expected to provide a suitable database for modeling of rod bundles and to allow development of mechanistic models of subcooled boiling suitable for use in TRAC-M.

Dr. Dhir detailed his experimental work on subcooled flow boiling at low pressures. This work has been on-going for ~ four years. The program is divided into seven elements (labeled Tasks) as follows:

- Literature Review
- Development of Database
- Test Plan for Experiments
- Design, Fabrication, and Testing With Flat Plate Geometry
- Design, Fabrication and Testing With Rod Bundle Geometry
- Preliminary Model Development
- Development of Validated Subcooled Flow Boiling Model

At this point, the work is focused on the last Task. Future work will involve generating void fraction data for flow boiling experiments with rod bundle geometry at pressures of 1-3 bars, mass flows of 100-1000 kg/m^{2}sec., and (subcooled) ΔTs of 0 to 50°C. The models and correlations will also be generalized to other pressures.

Subcommittee Comments on the above presentations included:

- Drs. Walls and Banerjee indicated that RES needed to design a framework to ensure that the UCLA data is successfully incorporated into TRAC-M vis-a-vis a robust model. It was also suggested that Dr. Dhir be enlisted into the model development effort.

- Messrs. Schrock and Wallis indicated that RES needs to provide more rigor with regard to what is shown in the experiments versus what the code model will look like.

SUBCOMMITTEE CAUCUS

- The Subcommittee praised the work performed by Dr. Dhir's team, and indicated that this information shows good promise for use in development of a mechanistic model of subcooled boiling.

FOLLOW-UP ACTIONS

- The Subcommittee Consultants will provide written comments regarding the draft regulatory guide, DG-1120, and the RES experimental program on subcooled nucleate boiling.

- The ACRS will review DG-1120 during its September 2002 Meeting.

BACKGROUND MATERIAL PROVIDED TO THE SUBCOMMITTEE PRIOR TO THE MEETING

1. Memorandum, P. Boehnert, ACRS, to ACRS Members and T/H Phenomena Subcommittee Consultants, Subject: ACRS Thermal-Hydraulic Phenomena Subcommittee Meeting, July 17-18, 2002 - Review of DG-1120 "Transient and Accident Analysis Methods" / Status of RES Experimental Program on Subcooled Flow Boiling Phenomena, dated July 1, 2002, and transmitting:

   - U.S. NRC Draft Regulatory Guide, DG-1120, "Transient and Accident Analysis Methods" dated June 2002.

   - Memorandum to F. Eltawila, RES, from G. Holahan, NRR, Subject: Office of Nuclear Reactor Regulation Comments on Revisions to DG-1096 and Draft SRP Section 15.0.2, undated

   - U.S. NRC Draft Standard Review Plan Section 15.0.2, Review of Transient and Accident Analysis Methods, dated December 2000

   - Draft Paper, "Onset of Nucleate Boiling and Active Nucleation Site Sensitivity during Subcooled Flow Boiling", M. Basu, et al., undated

   - Draft Paper, "Interfacial heat Transfer During Subcooled Flow Boiling", G. Warrier, et al., undated

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NOTE: Additional details of the open portions of this meeting can be obtained from a transcript of this meeting available for downloading or viewing via the ADAMS document management system, or can be purchased from Neal R. Gross & Co., Inc., 1323 Rhode Island Ave., NW, Washington, D.C., 20005, (202) 234-4433 (Voice), 387-7330 (Fax), E-Mail: "nrgross@nealrgross.com".

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE MEETING:
DRAFT REGULATORY GUIDE ON CODE DOCUMENTATION - DG-1120 /
RES T/H RESEARCH PROGRAM ON SUBCOOLED FLOW BOILING PHENOMENA
JULY 17, 2002
ROCKVILLE, MARYLAND

PRESENTATION SCHEDULE

Contact: P. Boehnert (301/415-8065; "pab2@nrc.gov")

TOPIC	PRESENTER	TIME
I. Introduction	**G. Wallis, Chairman**	8:30 a.m.
II. NRC-RES Presentations		
A. Draft Reg. Guide (DG-1120) - Transient & Accident Analysis Methods	**J. Staudenmeier, RES**	8:40 a.m.
1. Background (DG-1096) 2. Response to Public/Industry Comments		
	BREAK	10:30 a.m.
3. Content of DG-1120 4. Future Actions		
	LUNCH	12:30 p.m.
5. Additional Discussion (As Necessary)		1:30 p.m
B. UCLA Subcooled Flow Boiling Phenomena Research		
1. Introduction	**S. Bajorek, RES**	2:00 p.m.
2. Background / Literature Survey	**"V.J." Dhir, UCLA**	2:15 p.m.

TOPIC	**PRESENTER**	**TIME**
3. Experimental Facility & Test Sections	**“V.J.” Dhir**	2:30 p.m.
	BREAK	3:15 p.m.
4. Experimental Results	**“V.J.” Dhir**	3:30 p.m.
5. Model Development	**“V.J.” Dhir**	4:30 p.m.
III. Subcommittee Caucus 1. Comments on Meeting Presentations 2. Follow-on Actions 3. Decision to Bring Review Issues to ACRS/ Instructions to Presenters		5:45 p.m.
IV. Adjourn		6:00 p.m.

Project Leader (202–205–3032; *jtortorice@usitc.gov*), Amanda Horan, Deputy Project Leader (202–205–3459; *ahoran@usitc.gov*), or Richard Brown, Chief, Services and Investment Division (202–205–3438; *rbrown@usitc.gov*), Office of Industries, U.S. International Trade Commission, Washington, DC, 20436. For information on the legal aspects of this investigation, contact William Gearhart of the Office of the General Counsel (202–205–3091; *wgearhart@usitc.gov*). Hearing impaired individuals are advised that information on this matter can be obtained by contacting the TDD terminal on (202) 205–1810.

Background: As requested by the USTR, in its report the Commission will (1) describe the various activities involved in the provision of oil and gas field services; (2) describe the nature of trade in oil and gas field services; and (3) examine the extent of impediments to trade and potential benefits of trade liberalization. Since oil and gas field services are conducted in a large number of countries, USTR has requested that the Commission's study focus on issues that could be relevant multilaterally.

For the purpose of this study, oil and gas field services are broadly defined to include evaluation and exploration activities; drilling activities; and well development and completion activities. The letter follows similar requests made by the USTR in November 1999 and February 2001 for the Commission to conduct investigations on electric power services and natural gas services in selected foreign markets. The Commission submitted its report on electric power services to the USTR on November 23, 2000, and on natural gas services on October 16, 2001. Copies of these reports may be obtained by contacting the Office of the Secretary at 202–205–2000 or by accessing the USITC Internet server ww.usitc.gov). The USTR asked that the Commission furnish its report by March 18, 2003, and that the Commission make the report available to the public in its entirety.

Public Hearing: A public hearing in connection with the investigation will be held at the U.S. International Trade Commission Building, 500 E Street SW., Washington, DC, beginning at 9:30 a.m. on October 1, 2002. All persons shall have the right to appear, by counsel or in person, to present information and to be heard. Requests to appear at the public hearing should be filed with the Secretary, United States International Trade Commission, 500 E Street SW., Washington, DC 20436, no later than 5:15 p.m., September 17, 2002. Any prehearing briefs (original and 14 copies) should be filed not later than 5:15 p.m., September 19, 2002; the deadline for filing post-hearing briefs or statements is 5:15 p.m., October 22, 2002. In the event that, as of the close of business on September 17, 2002, no witnesses are scheduled to appear at the hearing, the hearing will be canceled. Any person interested in attending the hearing as an observer or non-participant may call the Secretary of the Commission (202–205–1806) after September 17, 2002, for information concerning whether the hearing will be held.

Written Submissions: In lieu of or in addition to participating in the hearing, interested parties are invited to submit written statements (original and 14 copies) concerning the matters to be addressed by the Commission in its report on this investigation. Commercial or financial information that a submitter desires the Commission to treat as confidential must be submitted on separate sheets of paper, each clearly marked "Confidential Business Information" at the top. All submissions requesting confidential treatment must conform with the requirements of section § 201.6 of the Commission's Rules of Practice and Procedure (19 CFR 201.6). All written submissions, except for confidential business information, will be made available in the Office of the Secretary to the Commission for inspection by interested parties. The Commission will not include any confidential business information in the report it sends to the USTR. To be assured of consideration by the Commission, written statements relating to the Commission's report should be submitted to the Commission at the earliest practical date and should be received no later than the close of business on October 22, 2002. All submissions should be addressed to the Secretary, United States International Trade Commission, 500 E Street SW., Washington, DC 20436. The Commission's rules do not authorize filing submissions with the Secretary by facsimile or electronic means. Persons with mobility impairments who will need special assistance in gaining access to the Commission should contact the Office of the Secretary at 202–205–2000. General information concerning the Commission may also be obtained by accessing its Internet server (*http://www.usitc.gov*).

List of Subjects

WTO, GATS, Oil and gas field services.

Issued: July 9, 2002.

By order of the Commission.

Marilyn R. Abbott,

Secretary to the Commission.

[FR Doc. 02–17644 Filed 7–12–02; 8:45 am]

BILLING CODE 7020–02–P

NUCLEAR REGULATORY COMMISSION

Advisory Committee on Reactor Safeguards

Subcommittee Meeting on Thermal-Hydraulic Phenomena; Notice of Meeting

The ACRS Subcommittee meeting on Thermal-Hydraulic Phenomena scheduled for July 17–18, 2002 has been changed to a one day meeting, which will be held on Wednesday, July 17, 2002 at 8:30 a.m. in Room T–2B3, 11545 Rockville Pike, Rockville, Maryland.

The Subcommittee will continue its review of the NRC Office of Nuclear Regulatory Research (RES) draft Regulatory Guide, DG–1120, "Transient and Accident Analysis Methods". The Subcommittee will also discuss the status of the RES experimental program pertaining to subcooled flow boiling phenomena.

Notice of this meeting was published in the **Federal Register** on Tuesday, July 2, 2002 (67 FR 44478). All other items pertaining to this meeting remain the same as previously published.

For further information contact: Mr. Paul A. Boehnert, Senior Staff Engineer (telephone 301–415–8065 or e-mail: *PAB2@nrc.gov*) between 7:30 a.m. and 5 p.m. (EDT).

Dated: July 9, 2002.

Sher Bahadur,

Associate Director for Technical Support.

[FR Doc. 02–17645 Filed 7–12–02; 8:45 am]

BILLING CODE 7590–01–P

NUCLEAR REGULATORY COMMISSION

Regulatory Guides; Withdrawal

The Nuclear Regulatory Commission is withdrawing Draft Regulatory Guide DG–4006, "Demonstrating Compliance with the Radiological Criteria for License Termination," from consideration as a regulatory guide. DG–4006 was published for public comment in August 1998.

This draft guide was issued to propose guidance on demonstrating compliance with radiological criteria at the sites of licensees who wish to terminate their licenses and release their sites. Appendix D of NUREG–1727,

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
SUBCOMMITTEE MEETING ON THERMAL-HYDRAULIC PHENOMENA

JULY 17, 2002
Date

PLEASE PRINT

ATTENDEES PLEASE SIGN-IN FOR THE MEETING

NAME	NRC ORGANIZATION
Joseph Staudenmeier	RES/DSARE/SMSAB
Akira Tokuhiro	RES/DSARE/SMSAB
RALPH CARUSO	NRR/SRXB
Jack Rosenthal	USNRC/RES/SMSAB

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DRAFT REGULATORY GUIDE DG-1120
-
TRANSIENT AND ACCIDENT ANALYSIS METHODS

Advisory Committee on Reactor Safeguards
July 17, 2002

Joseph Staudenmeier
Safety Margins and Systems Analysis Branch, RES

PURPOSE

Present the background and content of DG-1120 (formerly DG-1096), a regulatory guide for transient and accident methods used to analyze events required in 10 CFR 50.34 and defined in SRP chapter 15 and other chapters.

OUTLINE

1. Background and Need
2. Contents of DG-1096
3. Response to Public Comments
4. New Content in DG-1120
5. Status and Summary

BACKGROUND AND NEED

The Maine Yankee Independent Safety Assessment Team (ISAT) identified the need for NRC to provide guidance on transients and accident methods to:

1. Ensure sufficiency and consistency in the level of documentation and validation, and
2. Have a documented process in place to identify and rank key phenomena for relevant events, which is then used in the code development and assessment process.

- To implement this, the NRR Maine Yankee Lessons Learned Task Group recommended development of:

  1. A standard review plan section for code review, and
  2. A regulatory guide for code development and assessment.

DG-1096 CONTENTS

- In December 1998 the following proposals were made to the ACRS T/H subcommittee regarding the reg. guide:
    - Address analysis methods for all events on a generic basis stressing verification, validation, documentation, and quality assurance.
    - Describe application of the evaluation model concept which includes all computer programs, analysis methods not included in the computer programs, and other information used to show compliance with analyses required by 10CFR50.34.
    - Describe an acceptable evaluation model development and assessment process based on Code Scaling, Applicability, and Uncertainty (CSAU) principles refined over the last dozen years.
- The proposed content was incorporated into DG-1096.
- The evaluation model development process includes development methods based on the hierarchical system decomposition principles, largely inspired by the Severe Accident Scaling Methodology (SASM).

DG-1096 TABLE OF CONTENTS

A. INTRODUCTION

B. DISCUSSION

C. REGULATORY POSITION

1. EVALUATION MODEL DEVELOPMENT AND ASSESSMENT PROCESS (EMDAP)
2. QUALITY ASSURANCE
3. DOCUMENTATION
4. GENERAL PURPOSE COMPUTER PROGRAMS

D. IMPLEMENTATION

NOMENCLATURE AND DEFINITIONS

REFERENCES

Appendix A ADDITIONAL CONSIDERATIONS IN THE USE OF THIS REGULATORY GUIDE FOR ECCS ANALYSIS

REGULATORY ANALYSIS

PRINCIPLES OF EVALUATION MODEL DEVELOPMENT AND ASSESSMENT

1. Determine requirements for the evaluation model and the importance of key systems, components, processes and phenomena. A process like the hierarchical system decomposition should be used to assure that all levels of evaluation model development are properly considered.

2. Develop an evaluation model that meets the requirements.

3. Develop an assessment base appropriate to the requirements and the evaluation model. (SA of CSAU)

4. Assess the adequacy of the evaluation model in light of analytical and experimental uncertainties. (U of CSAU)

5. Establish and follow an appropriate quality assurance protocol during the evaluation model development and assessment process.

6. Provide comprehensive, accurate, up-to-date documentation.

RESOLUTION OF PUBLIC COMMENTS

- DG-1096 was issued for public comment in December 2000. (13 sets of comments received)
- A Public Workshop was held in April 2001 to discuss the public comments.
- Revisions to DG-1096 were completed in February 2002 and provided to NRR for comment.
- NRR comments received June 2002.

SIGNIFICANT REVISIONS TO DG-1096

Added section on a graded approach to applying the EMDAP for modifications to existing evaluation models. (Numerous comments)

changed SRP chapter 15 events to SRP events since all events are not in chapter 15. (e.g. LTOP) (NRC)

made changes to A.3 to remove indications of bias against uncertainty methods other than CSAU (GNF)

page 3, the definition of a computer code is expanded to include calculations performed with spreadsheets and tools such as MathCAD or Mathematica.(CEOG)

page 2, Added reference to list of definitions in introduction(CEOG)

page 2, changed "new model" to "unapproved model" to remove ambiguity (CEOG)

reworded page 4 , item 2 (NRC)

reworded page 4, item 4 (CEOG)

page 30, added a third type of uncertainty to the definition. (CEOG)

SIGNIFICANT REVISIONS TO DG-1096 (cont.)

section 1.1.1 clarified scenario dependency on plant class specific and plant specific. (BWROG) (WOG)

section 1.2.3 added additional information about data selection for correlation development and assessment. (BWROG)

section 1.4.8 made connection from step 20 reference to step 16 clear. (BWROG)

section 1.4.8 Added discussion about treatment of “suitably conservative input” to allow best estimate + uncertainty treatment of parameters. (BWROG)

section 3.6 added instruction to document convergence studies in the assessment manual. (BWROG)

Section 4. Clarified section on the use of general purpose computer codes and generic assessment. (BWROG)

Clarified support for use of plant data in code assessments. (BWROG)

Clarified scope of reg guide. (WOG)

DG-1120 TABLE OF CONTENTS

GRADED APPROACH TO APPLYING THE EMDAP

Application of the full EMDAP described in this regulatory guide may not be needed for all evaluation models submitted for review by the staff. Some evaluation models submitted for review are relatively minor modifications to existing evaluation models. The scope and depth of applying the development process to the evaluation model should be based on a graded approach. The following five attributes of the evaluation model should be considered when determining the extent to which the full model development process may be reduced for a specific application:

- Novelty of the revised evaluation model compared to the currently acceptable model.
- The complexity of the event being analyzed.
- The degree of conservatism in the evaluation model.
- The risk significance or safety importance of the event.
- The extent of any plant design or operational changes that would require a re-analysis.

GRADED APPROACH TO APPLICATION OF DG-1096 DEVELOPMENT AND ASSESSMENT PROCESS (EMDAP)

Full Application		**Property**		**Minimum Application**
Completely new evaluation model	←	Novelty of evaluation model	→	No change to evaluation model
Complex event (e.g. LBLOCA)	←	Complexity of event	→	Simple Event (e.g. increase FW flow)
Best estimate model and application	←	Conservatism of application	→	Manifestly conservative model and application
High	←	Risk importance of event	→	Very low
Uniquely new plant design	←	Extent of plant change	→	Small tech spec change

CONSERVATISM IN EVALUATION MODELS

Many comments stated that the current evaluation models have a large degree of conservatism and therefore do not need to undergo the full EMDAP process.

Close examination of the claims of model conservatism reveal that most of the conservatism lies in the input assumptions.

Question: How can the degree of conservatism in the evaluation model be demonstrated without a full CSAU analysis?

The Regulatory Guide proposes a simplified method to demonstrate the degree of conservatism in evaluation models.

SIMPLIFIED METHOD TO DEMONSTRATE MODEL CONSERVATISM

A proposed simplified method to demonstrate the degree of conservatism in the model involves the following steps:

1. Perform an analysis of a plant transient or scaled test (e.g. LOFT transient tests) similar to the event in question in a best estimate mode to show the fidelity of the evaluation model.

2. Perform the analysis of the same transient or test using the evaluation model assumptions and compare the key figures of merit that determine the safety limit for the transient in question to the same calculated quantities in step 1.

3. Perform an analysis of the event used in the safety limit calculation with initial conditions set at the appropriate tech spec limits in best estimate mode.

4. Perform an analysis of the event used in the safety limit calculation using the evaluation model assumptions and compare the key figures of merit that determine the safety limit for the event to the calculated quantities in step 3 to show the degree of conservatism in the model.

5. Evaluate the change in the key figure of merit due to the model change and compare it to the estimated degree of conservatism in the models determined by performing steps 1-4.

STATUS AND SUMMARY

- DG-1120 on transient and accident analysis methods addresses the findings of the Maine Yankee panels and other review groups.
- Timely inclusion of current ACRS comments is the next step in the process of eventually releasing DG-1120 for public comment.
- After incorporation of ACRS comments, DG-1120 and the regulatory analysis will be sent to OGC for concurrence and then to CRGR for review.
- After appropriate OGC and CRGR consent, the documents will be released for public comment.

United States Nuclear Regulatory Commission

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Subcooled Boiling Experimental Program in Support of TRAC-M Model Improvement

Presentation to the ACRS Subcommittee on Thermal-Hydraulic Phenomena

July 17, 2002

Stephen M. Bajorek
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

Example: Large CLL oscillations due to pressure sensitive subcooled boiling model "bubble pumping" term.

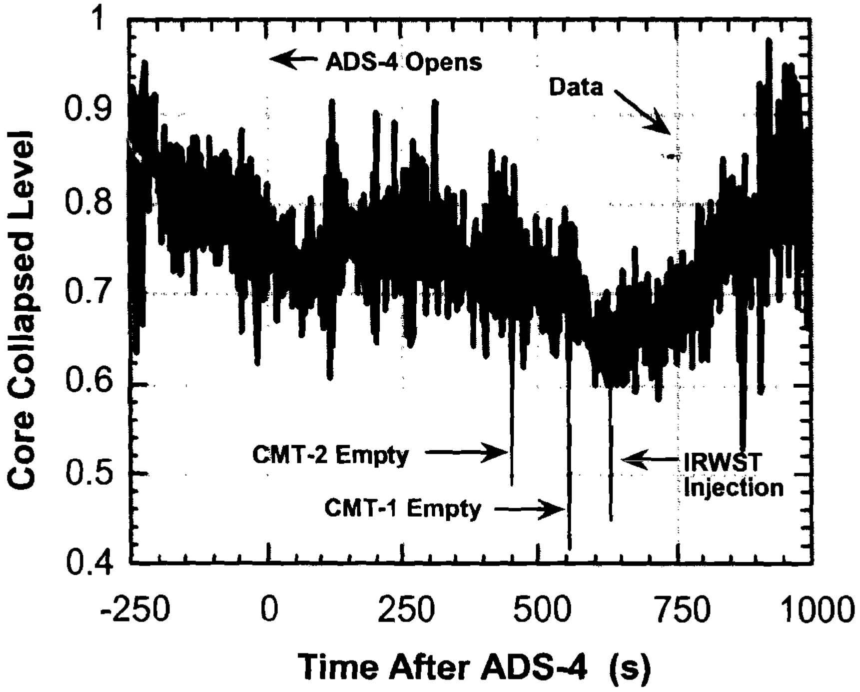

FIGURE V-9: Early RELAP5 calculation of core collapsed level for an SBLOCA in the OSU facility illustrating "numerical noise".

Conclusions

- **Existing subcooled boiling model in TRAC-M, which is similar to those used other two-fluid codes, lacks an acceptable basis and relys on several "ad-hoc" ramps to achieve heat-flux splitting.**

- **Experimental program at UCLA is being conducted to provide a suitable database for rod bundles and to develop mechanistic models for subcooled boiling suitable for TRAC-M.**

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SUBCOOLED FLOW BOILING AT LOW PRESSURES

EXPERIMENTS AND MODEL DEVELOPMENT

N. BASU, G. WARRIER, AND V. K. DHIR
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
UNIVERSITY OF CALIFORNIA, LOS ANGELES

PRESENTED AT ACRS MEETING, ROCKVILLE, ON JULY 17, 2002

OBJECTIVES

- To develop a mechanistic basis for subcooled flow boiling heat transfer for incorporation in advanced reactor system codes
- Support the development with laboratory scale experiments on a nine-rod bundle
- Range of parameters of interest in the experiments
  - Pressure (P) - 1 to 5 *bar*
  - Mass flux (G) - 100 to 1000 kg/m^2s
  - Inlet liquid subcooling (ΔT_{sub}) - 0 to 50 ^oC

OBJECTIVES (contd.)

- To accomplish these objectives, the following tasks have been identified:
  - Task 1. Literature review
  - Task 2. Development of database
  - Task 3. Test plan for experiments
  - Task 4. Design, fabrication, and testing with flat plate geometry
  - Task 5. Design, fabrication, and testing with rod bundle geometry
  - Task 6. Preliminary model development
  - Task 7. Development of validated subcooled flow boiling model

TASK 1

LITERATURE REVIEW

- A thorough search of the open literature was performed
- Though a number of models/correlations have been developed, most have a great deal of empiricism built into them and are not accurate or consistent at the subprocess level
- Application of these models to low pressures is suspect
- Very limited low pressure experimental data are available to validate the models

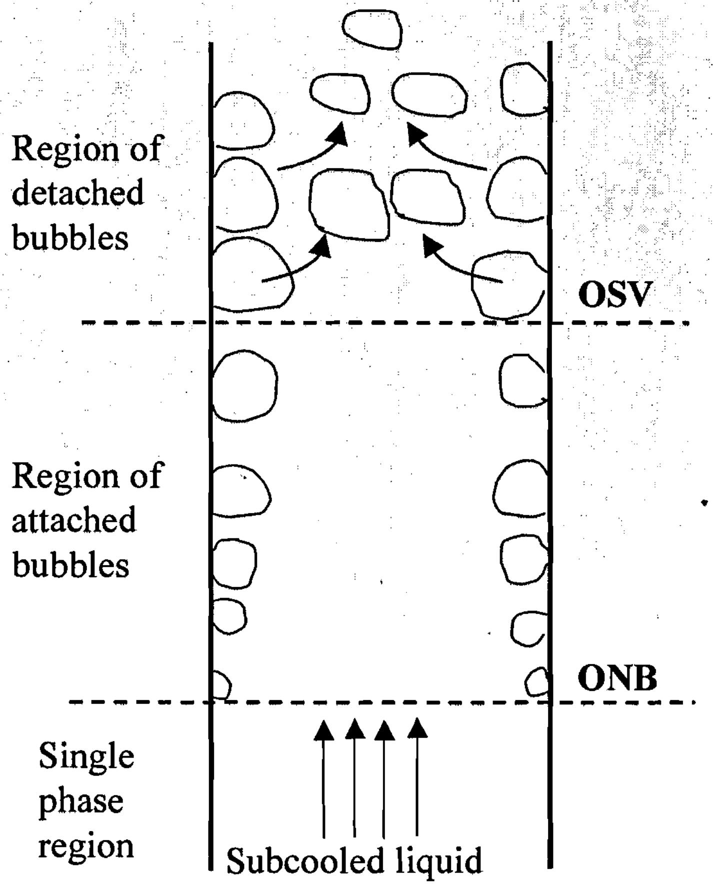
TASK 2

DATABASE DEVELOPMENT

- The relevant data was compiled and documented
- A database titled “Experimental and Analytical Studies in Subcooled Flow Boiling” was developed and submitted to NRC

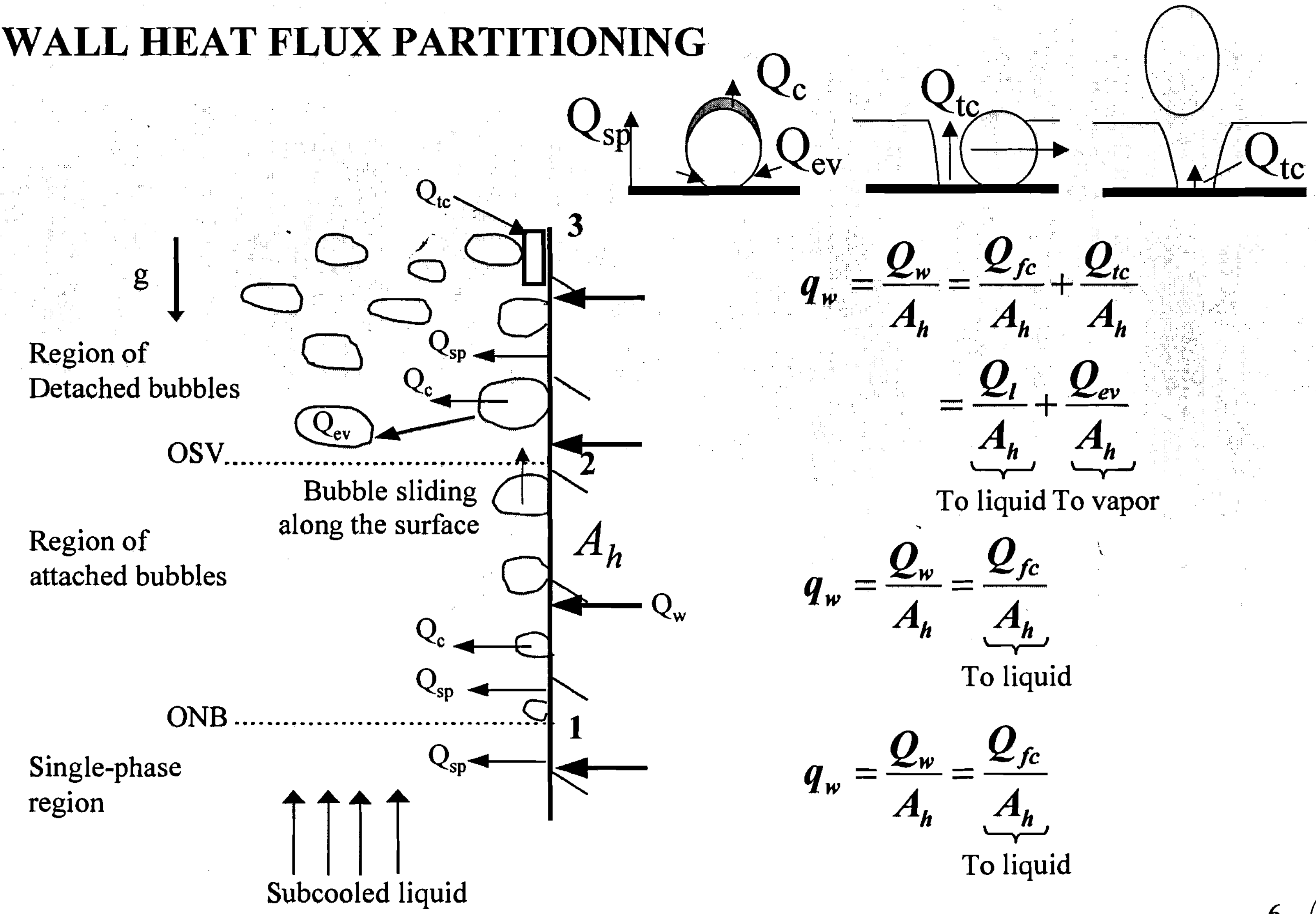
TASK 3
TEST PLAN FOR EXPERIMENTS

- Since the available data is scarce and moreover do not cover the range of parameters of interest, validation of models is difficult
- Additional experiments are required
- Based on the literature review, the key issues to be addressed include the following:
  - Wall heat flux partitioning
  - Interfacial heat transfer



TASK 6. PRELIMINARY MODEL DEVELOPMENT

WALL HEAT FLUX PARTITIONING



$$q_w = \frac{Q_w}{A_h} = \frac{Q_{fc}}{A_h} + \frac{Q_{tc}}{A_h}$$

$$= \underbrace{\frac{Q_l}{A_h}}_{\text{To liquid}} + \underbrace{\frac{Q_{ev}}{A_h}}_{\text{To vapor}}$$

$$q_w = \frac{Q_w}{A_h} = \underbrace{\frac{Q_{fc}}{A_h}}_{\text{To liquid}}$$

$$q_w = \frac{Q_w}{A_h} = \underbrace{\frac{Q_{fc}}{A_h}}_{\text{To liquid}}$$

WALL HEAT FLUX PARTITIONING (contd.)

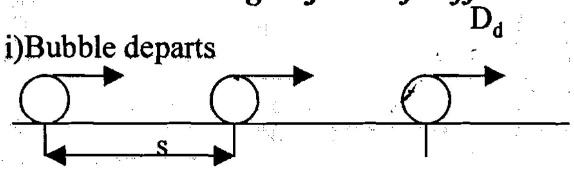
Case I. (Isolated bubbles)

$D_d, D_l \le 1/\sqrt{Na}$

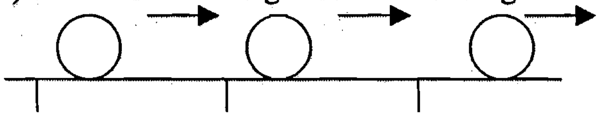
Spacing $s = 1/\sqrt{Na}$

Bubbles sliding before lift off

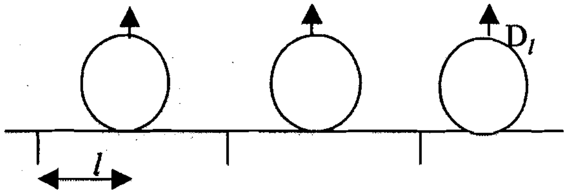
i)Bubble departs



ii) Bubble slides and grows while sliding

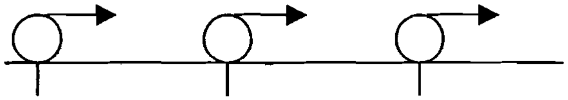


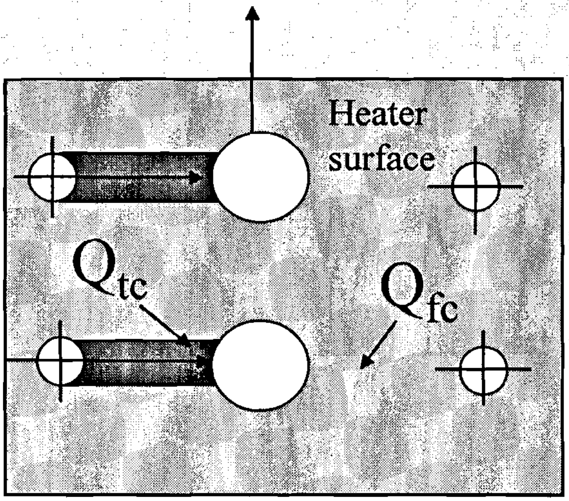
iii) Bubble lifts off after sliding for a distance *l*



iv) Next set of bubble inception occurs

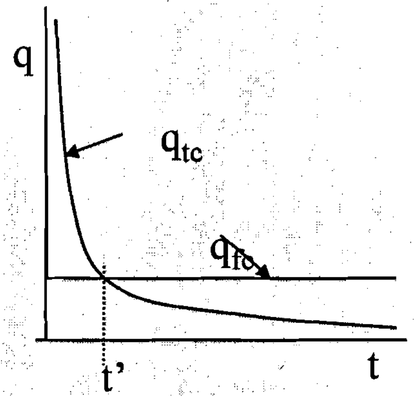
v) Bubble grows at its site of origin and departs when it attains size D$_d$





WALL HEAT FLUX PARTITIONING (contd.)

Transient conduction component



- **Heating of the liquid due to disruption of the boundary layer by bubble sliding and eventually lifting off.**
- ***t'* : time over which transient conduction will occur before steady state forced convection heat transfer takes over.**

$$\frac{Q_{tc}}{A_h} = \frac{1}{t_w + t_g}\int_0^t \frac{k}{\sqrt{\pi\alpha_l t}}\left(\Delta T_w + \Delta T_{sub}\right)\left(A_{sl}\right)N_a dt$$

(i) $t = t'$ when $t' < (t_w + t_g)$

Forced convection for time t' to (tw+tg) over sliding area

(ii) $t = t_g + t_w$ when $t' \geq (t_g + t_w)$

f - bubble release frequency $= 1/(t_g + t_w)$ t_g -growth time t_w -waiting time

$A_{sl} = C\, D_l\, l$, Area swept by a sliding bubble, A_h – Heater surface area

N_a - active nucleation site density, D_l -bubble lift-off diameter, l - sliding distance

C – ratio of base diameter of bubble influence with the lift-off diameter. A value of 85% for C is empirically obtained.

WALL HEAT FLUX PARTITIONING (contd.)

Forced convection component

Convective heating of the liquid occurs over all areas of the heater surface except those occupied by bubbles and under transient conduction

$$\frac{Q_{fc}}{A_h} = \overline{h_{fc}}(\Delta T_w + \Delta T_{sub})\underbrace{[1 - A_{sl}N_a]}_{\text{Heater area not affected by bubbles}} + \underbrace{\overline{h_{fc}}(\Delta T_w + \Delta T_{sub})A_{sl}N_a\left(1 - \frac{t'}{t_w + t_g}\right)}_{\text{Additional term occurs when } t' < (t_w + t_g)}$$

h_{fc} : single phase heat transfer coefficient. Standard correlations are corrected to account for the presence of bubbles, which increases the roughness of the heater surface.

WALL HEAT FLUX PARTITIONING (contd.)

Condensation component (stationary and sliding bubbles)

$$\frac{Q_c}{A_h} = \overline{h_c A_c} N_a \Delta T_{sub}$$

$$\overline{h_c A_c} = \frac{1}{\left(t_w + t_g\right)} \left[\underbrace{\int_{t_1}^{t_g} h_c(t) A_c(t) dt}_{\text{Condensation during bubble growing at its site}} + \underbrace{\int_{t_g}^{t_g+t_s} h_c(t) A_c(t) dt}_{\text{Condensation during sliding}} \right]$$

h_c : condensation heat transfer coefficient.
can be modeled assuming forced convection over a portion of a sphere

A_c : surface area for condensation.

t_1= time at which condensation begins while bubble grows at its site of origin

t_s= sliding time

$$\overline{h_c A_c} \approx \frac{1}{\left(t_w + t_g\right)} \int_{0}^{t_g} h_c(t) A_c(t) dt$$

WALL HEAT FLUX PARTITIONING (contd.)

$$\frac{Q_w}{A_h} = \frac{Q_{fc}}{A_h} + \frac{Q_{tc}}{A_h} = \underset{\substack{\text{Direct heating}\\ \text{of bulk liquid}}}{\frac{Q_{bulk}}{A_h}} + \underbrace{\underset{\substack{\text{Indirect heating}\\ \text{of bulk liquid.}}}{\frac{Q_c}{A_h}} + \underset{\text{To vapor}}{\frac{Q_{ev}}{A_h}}}_{\text{Energy going to the bubble}} = \frac{Q_l}{A_h} + \frac{Q_{ev}}{A_h}$$

Evaporative component

Energy carried away from the surface by bubbles lifting off

$$\frac{Q_{ev}}{A_h} = \rho_v h_{fg} \frac{\pi}{6} D_l^3 N_a f$$

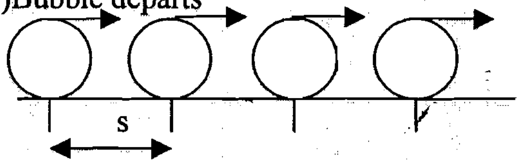
WALL HEAT FLUX PARTITIONING (contd.)

Bubble merger cases

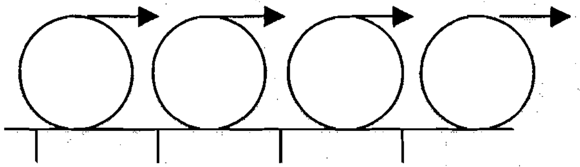
Case II. $D_d < 1/\sqrt{Na}, D_l \geq 1/\sqrt{Na}$

Bubbles sliding,followed by merging before lift off

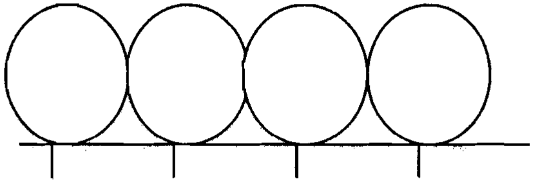
i)Bubble departs



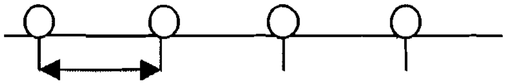
ii) Bubble slides and grows while sliding



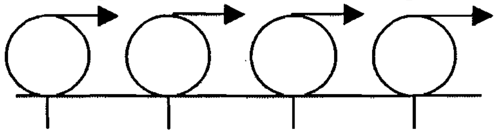
iii) Bubbles grow to the size of spacing length, merge to give one lift off diameter bubble



iv) Next set of bubble inception occurs



v) Bubble grows in their site of origin and departs

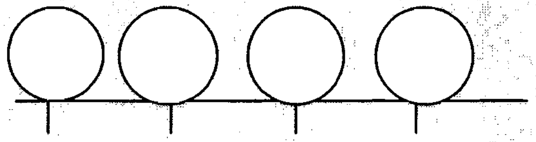


Case III. $D_d \geq 1/\sqrt{Na}$

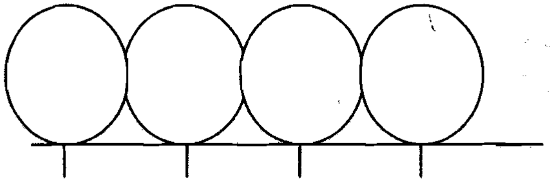
No sliding case, bubbles merge before lift off

i) bubble inception occurs

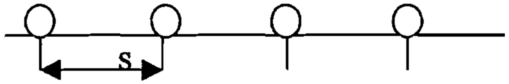
ii) Bubbles grow at the sites



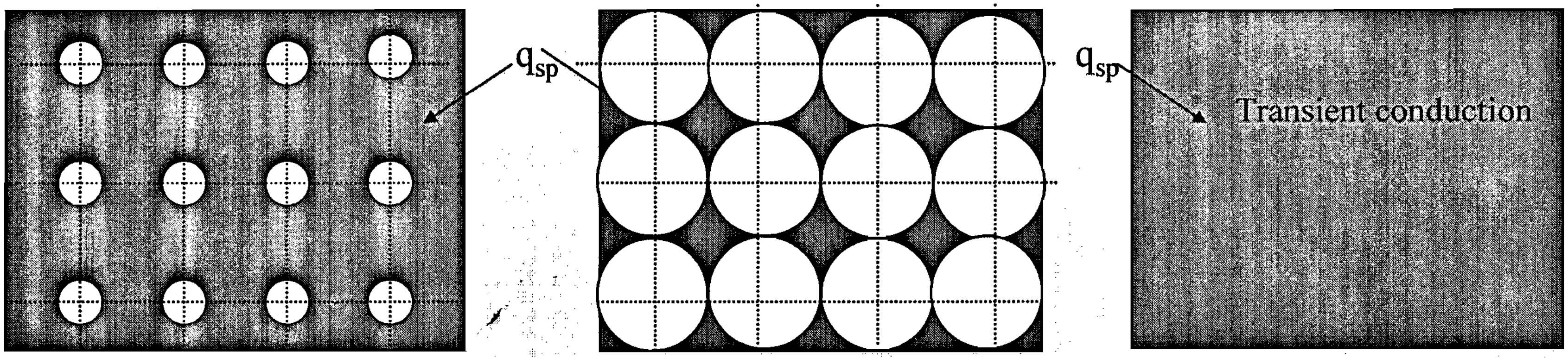
iii) Bubbles grow to the size of spacing length, merge to give one lift off diameter bubble



iv) Next set of bubble inception occurs



WALL HEAT FLUX PARTITIONING (contd.)



when $t' \leq t_w$

Transient conduction component

$$\frac{Q_{tc}}{A_h} = \frac{1}{t_w + t_g}\int_0^{t'} \frac{k}{\sqrt{\pi\alpha_l t}}\left(\Delta T_w + \Delta T_{sub}\right)dt$$

Forced convection component

$$\frac{Q_{fc}}{A_h} = \overline{h_{fc}}\left(\Delta T_w + \Delta T_{sub}\right)\frac{t_w - t'}{(t_g + t_w)} + \overline{h_{fc}}\left(\Delta T_w + \Delta T_{sub}\right)\left[1 - A_b N_a\right]\frac{t_g}{(t_g + t_w)}$$

$A_b = \frac{\pi}{4}(Cs)^2$ Bubble base area

WALL HEAT FLUX PARTITIONING (contd.)

when $t' > t_w$

Transient conduction component

$$\frac{Q_{tc}}{A_h} = \frac{1}{t_w + t_g}\left[\begin{array}{l}\int_0^{t_w} \frac{k}{\sqrt{\pi \alpha_l t}}(\Delta T_w + \Delta T_{sub})dt + \\ \int_{t_w}^{t} \frac{k}{\sqrt{\pi \alpha_l t}}(\Delta T_w + \Delta T_{sub})[1 - A_b N_a]dt\end{array}\right]$$

$t=t_g+t_w$ **if** $t' > t_g+t_w$, **else** $t=t'$.

Forced convection component

$$\frac{Q_{fc}}{A_h} = \overline{h_{fc}}(\Delta T_w + \Delta T_{sub})[1 - A_b N_a]\frac{t_g + t_w - t'}{(t_g + t_w)}$$

for $t_w < t' < (t_w + t_g)$

=0, No forced convection

for $t' \geq (t_w + t_g)$

WALL HEAT FLUX PARTITIONING (contd.)

Condensation component (attached bubbles)

$$\frac{Q_c}{A_h} = \overline{h_c A_c} N_a \Delta T_{sub}$$

Evaporative component

$$\frac{Q_{ev}}{A_h} = \rho_v h_{fg} \frac{\pi}{6} D^3 N_a f$$

Here D = s(spacing length), maximum size bubble grows to before merging to attain lift off diameter size.

$f = 1/\ t_g + t_w$ will correspond to bubble of size s when $D_d > s$, otherwise will correspond to D_d.

$$\frac{Q_w}{A_h} = \frac{Q_{fc}}{A_h} + \frac{Q_{tc}}{A_h} = \underset{\text{Direct heating of bulk liquid}}{\frac{Q_{bulk}}{A_h}} + \underbrace{\underset{\text{Indirect heating of bulk liquid.}}{\frac{Q_c}{A_h}} + \underset{\text{To vapor}}{\frac{Q_{ev}}{A_h}}}_{\text{Energy going to the bubble}} = \frac{Q_l}{A_h} + \frac{Q_{ev}}{A_h}$$

INTERFACIAL HEAT TRANSFER

- Interfacial heat transfer mechanism of interest in subcooled boiling is the condensation occurring at liquid-vapor interfaces of bubbles
- For attached bubbles, condensation at bubble top provides an alternate route for transfer of sensible heat to bulk liquid - included in wall heat flux partitioning
- For detached bubbles, the condensation rate determines the rate of change of bubble size in the flow direction and also transfers sensible heat to bulk liquid
- Void fraction in flow direction is dependent on the bubble size and number density

PARAMETERS TO BE DETERMINED AND METHODS OF MEASUREMENT

No.	Quantity	Measurement Technique
1	Wall heat flux (q_w)	• From temperature gradient in the solid, or from power input to rods
2	Heater wall temperature (T_w)	• Miniature thermocouples embedded in heater block or attached to the inner wall of cladding
3	Liquid temperature profile (T_l)	• Traversable microthermocouple
4	Location of onset of nucleate boiling (*ONB*)	• Visual observation of boiling surface • Thermocouple output
5	Active nucleation site density (N_a)	• Pictures of heating surface • Counting the number of nucleation sites per unit area • Thermocouple output
6	Bubble departure & lift-off diameter (D_d & D_l)	• High-speed films of the bubble departure process • Measurement of the bubble size
7	Location of onset of significant void (*OSV*)	• Visual observation of boiling surface

PARAMETERS TO BE DETERMINED AND METHODS OF MEASUREMENT (contd.)

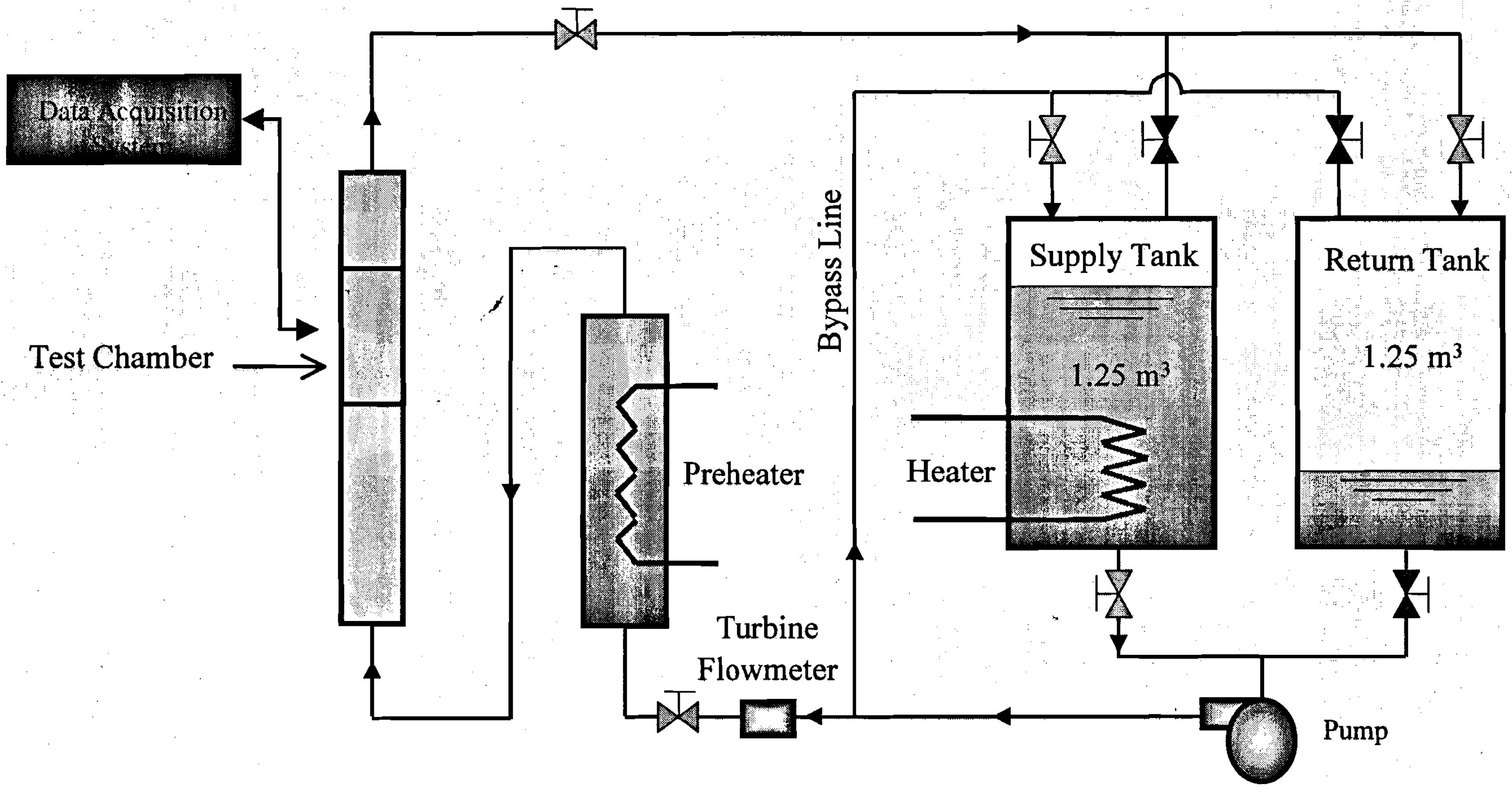
No.	Quantity	Measurement Technique
8	Bubble release frequency (f)	• High-speed films of the wall vapor generation process • Count the number of bubbles released per unit time
9	Condensation heat transfer coefficient for attached bubbles ($q_{c,att}$)	• Liquid temperature profile and bubble growth rate (from high-speed films) • Difference in bubble growth rate for saturated and subcooled boiling is proportional to condensation heat transfer rate • Need auxiliary experiments and analysis
10	Condensation heat transfer coefficient for detached bubbles ($q_{c,det}$)	• Liquid temperature profile, bubble relative velocity, and rate of bubble collapse (from high-speed films)
11	Bubble number density (N_b)	• High-speed films of bulk liquid • Count the number of bubbles per unit volume
12	Bubble relative velocity ($U_{b,rel}$)	• High-speed films of bubbles in liquid • Measure the distance traveled per unit time
13	Void fraction (α)	• Gamma densitometer

TASK 4

DESIGN, FABRICATION, AND TESTING WITH FLAT PLATE GEOMETRY

- Experimental facility with a flat plate heater geometry and a prototypical nine rod bundle geometry were designed and fabricated
- A total of 125 subcooled flow boiling experiments were performed on the flat plate covering the following range of parameters:
  - P: 1.03 bar
  - G: 124 to 898 kg/m^2s
  - $\Delta T_{sub,in}$: 5 to 50 ^oC
  - q_w: 2 to 113 W/cm^2
  - ϕ: 30^o to 90^o
- Relevant physical quantities were measured

EXPERIMENTAL FACILITY



Experimental Conditions

Vertical (Up) Subcooled Water Flow

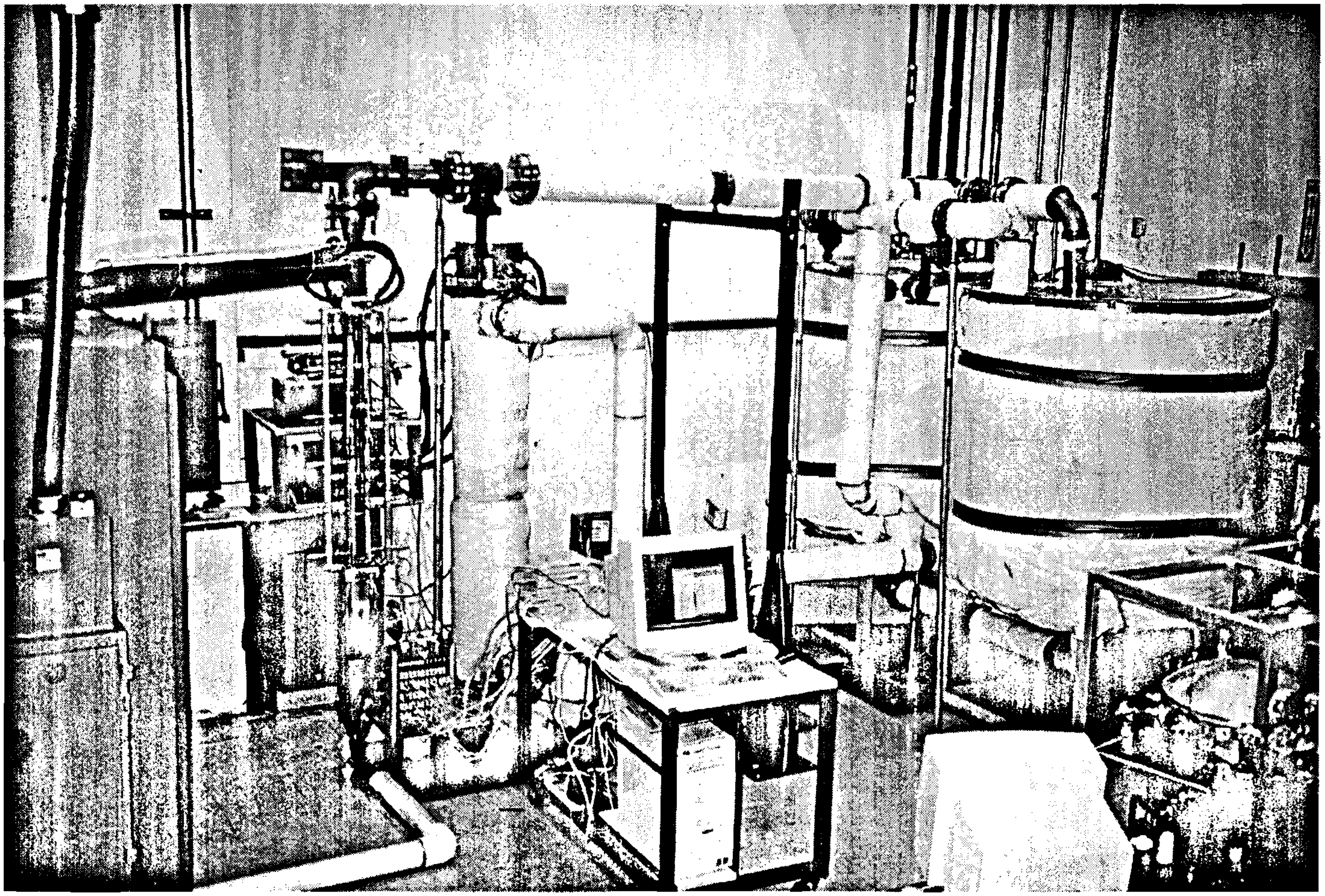
Test Surface Geometry

Flat Plate - 32 mm wide,
330 mm long
Rod bundle - 3 x 3,
11 mm OD, 914 mm long

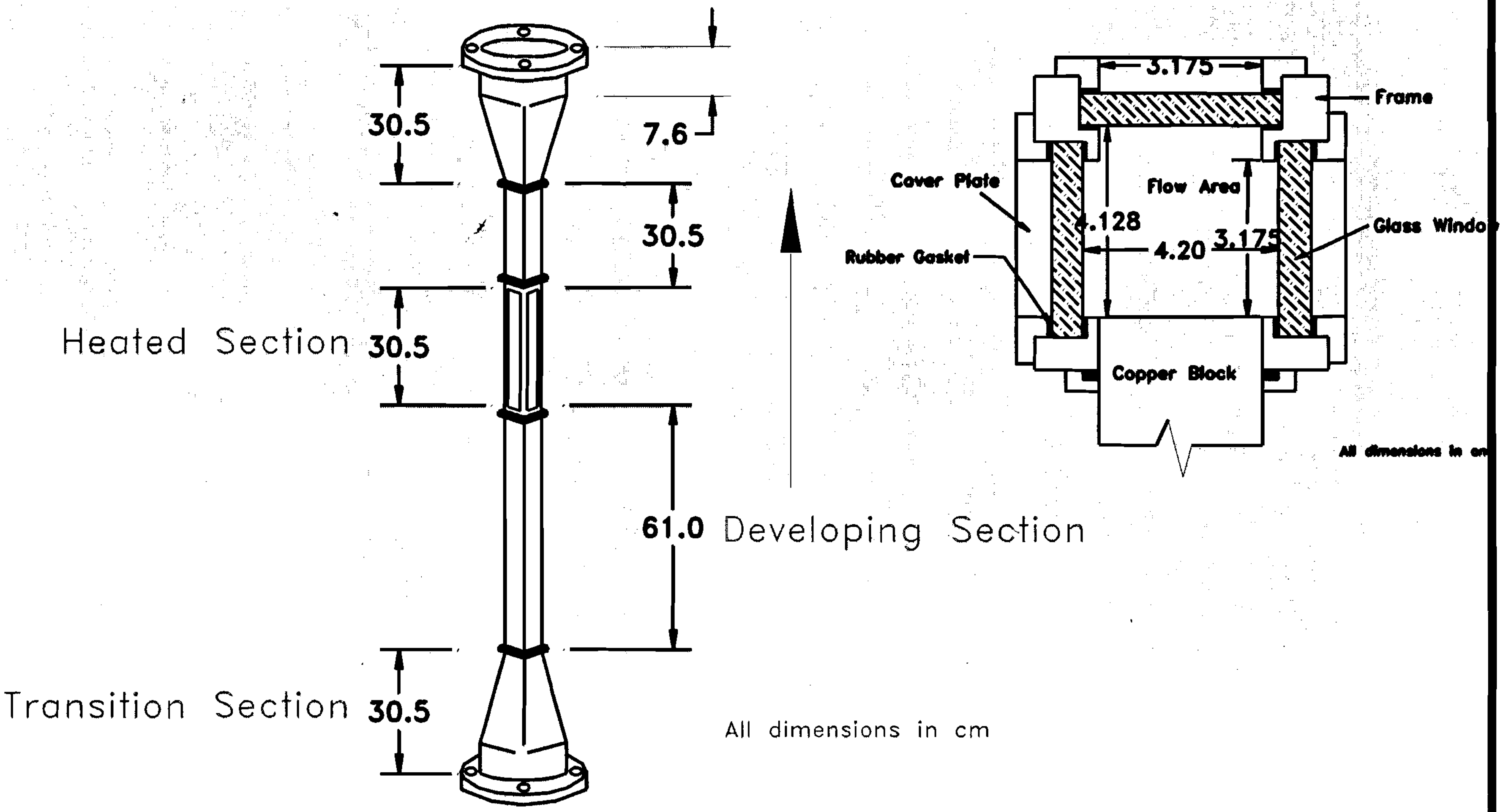
Measurement System

Miniature Thermocouples
Pressure Transducers
Gamma Densitometer
High-Speed Photography

FLOW BOILING TEST FACILITY

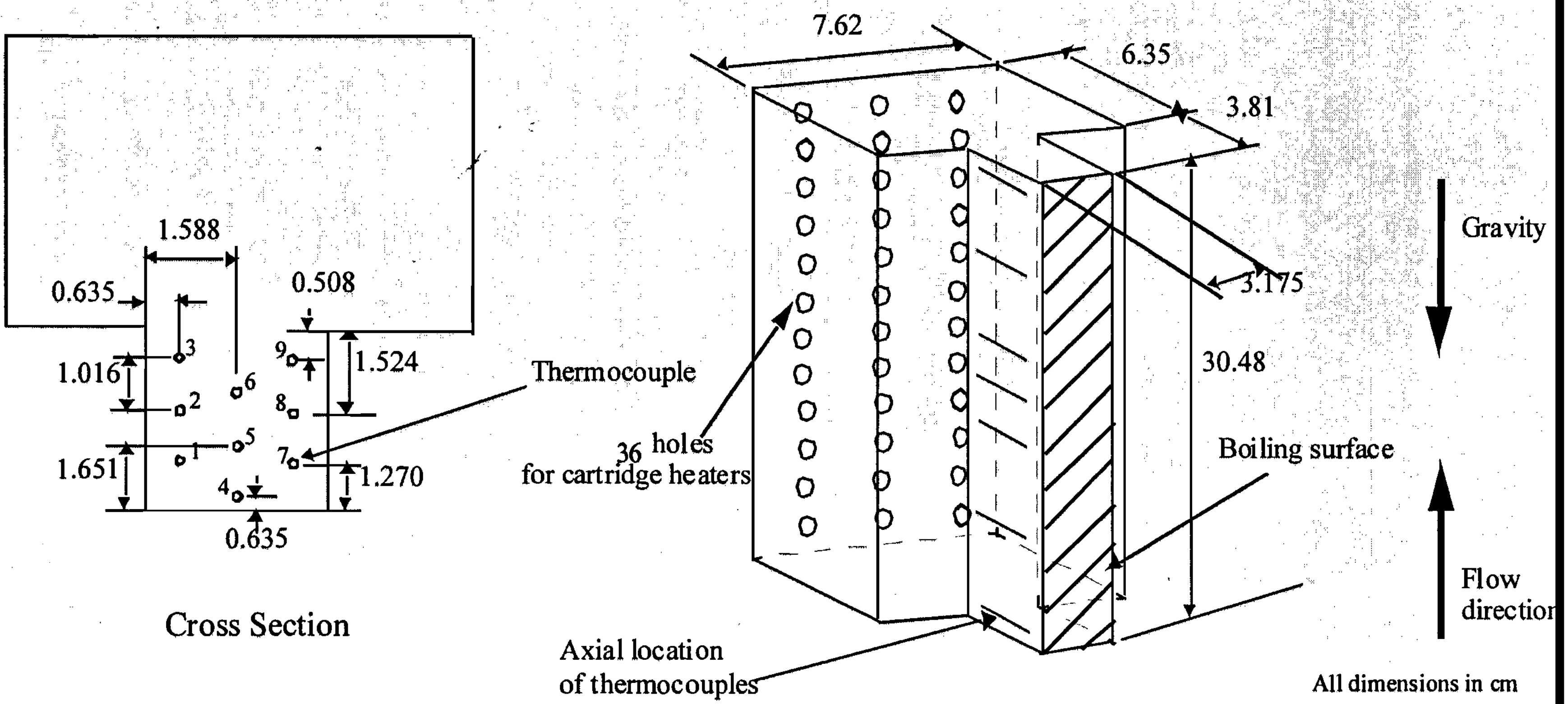


FLAT PLATE TEST SECTION



All dimensions in cm

FLAT PLATE HEATER



All dimensions in cm

TASK 5

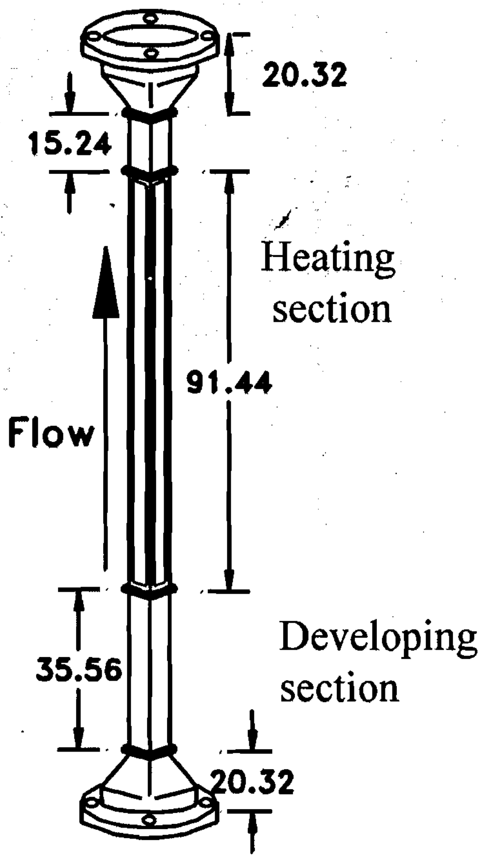
DESIGN, FABRICATION, AND TESTING WITH ROD BUNDLE GEOMETRY

- Nine rod bundle heater was designed and fabricated
- The rods are made of Zircalloy-4 (1.11 *cm* OD, 0.015 *cm* thickness) and are arranged in a 3 x 3 square grid
- A total of 140 subcooled flow boiling experiments were performed covering the following range of parameters:

P, bar :	1.03	2.0	3.2
G, $kg/m^2 s$	186 to 2800	336 to 926	346 to 916
$\Delta T_{sub,in}$, °C	2.7 to 69	25 to 50	30 to 46
q_w, W/cm^2	1.6 to 25	5 to 25	5 to 25
ϕ,(deg)	57	57	57
$D_h(cm)$	1.23	1.23	1.23

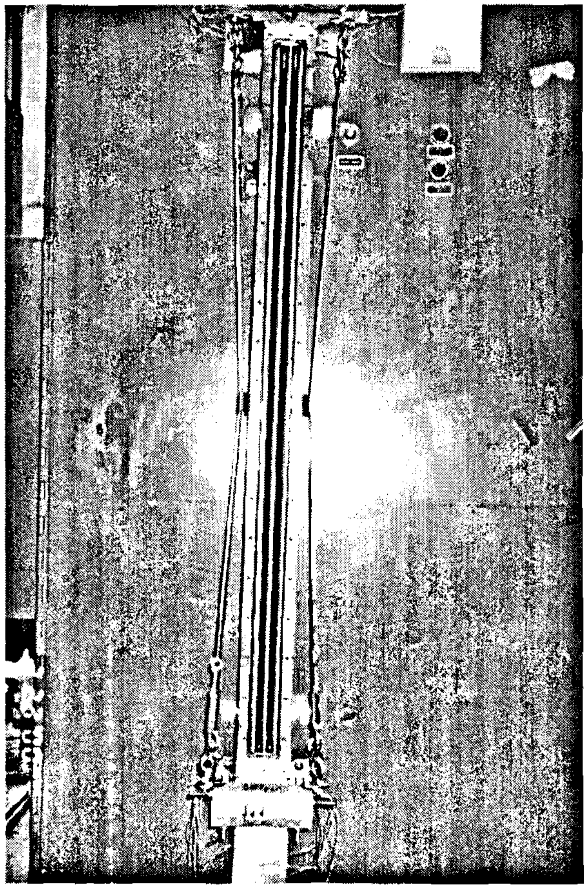
Relevant physical quantities were measured

ROD BUNDLE TEST SECTION



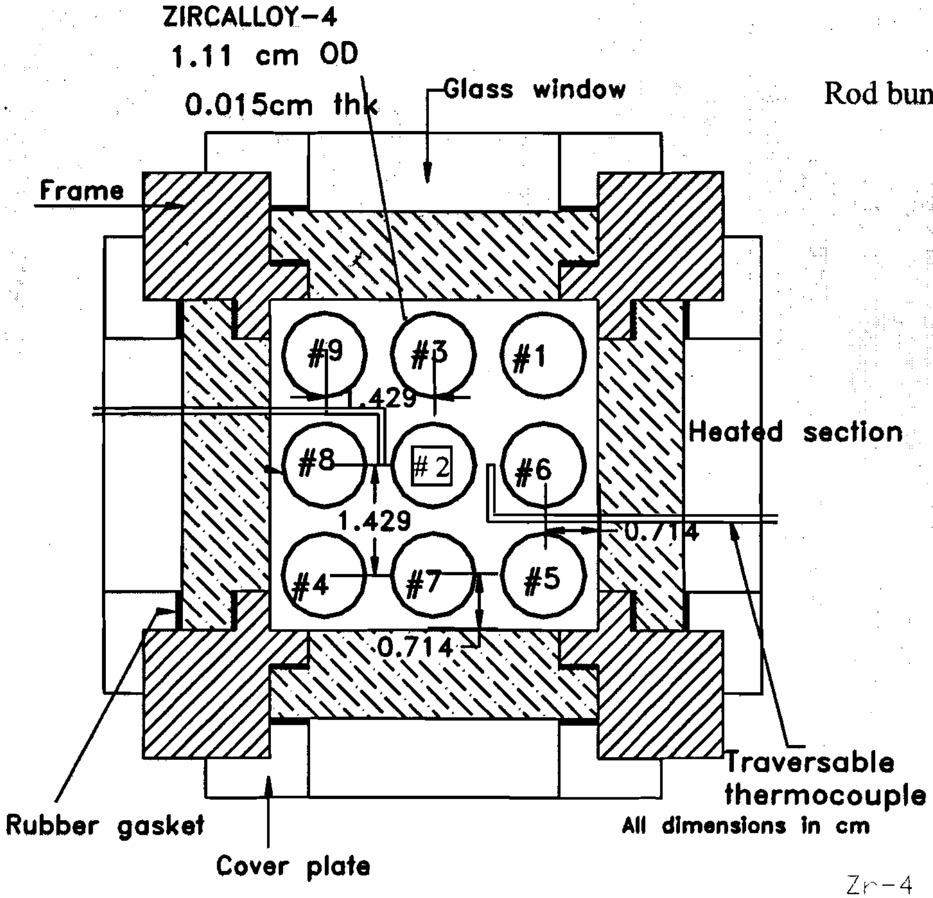
All dimensions
in cm

Test section

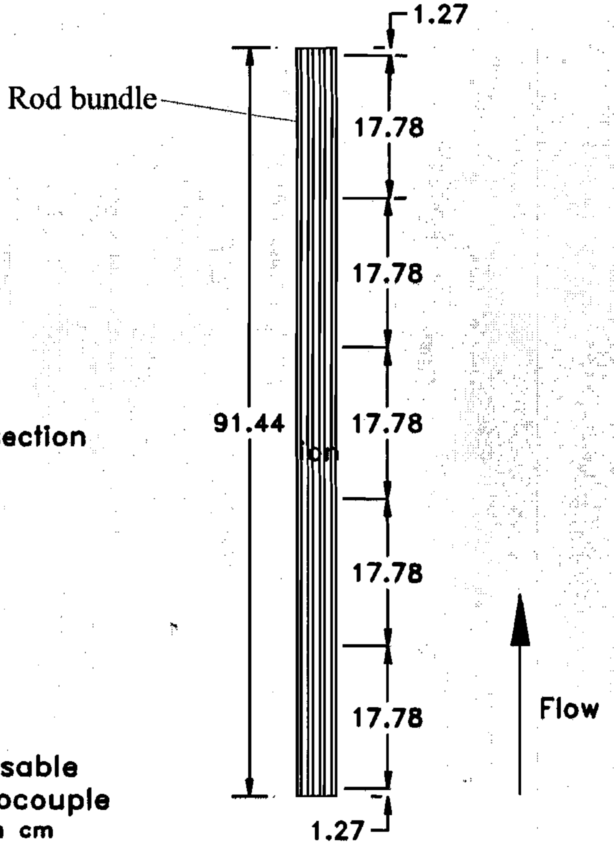


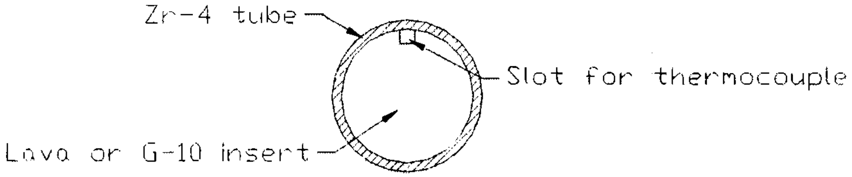
ROD BUNDLE HEATER

Cross section



Thermocouple placement





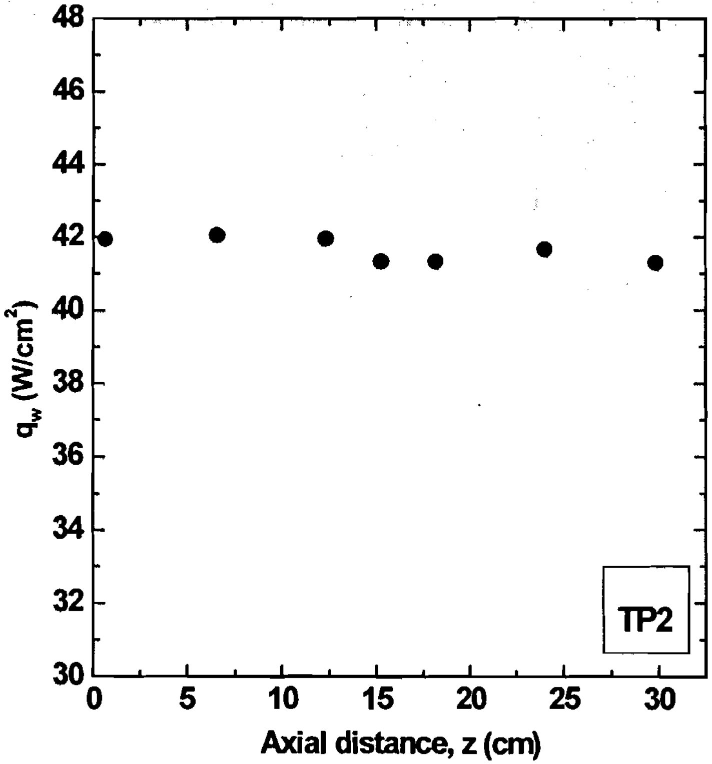
TASK 6

PRELIMINARY MODEL DEVELOPMENT

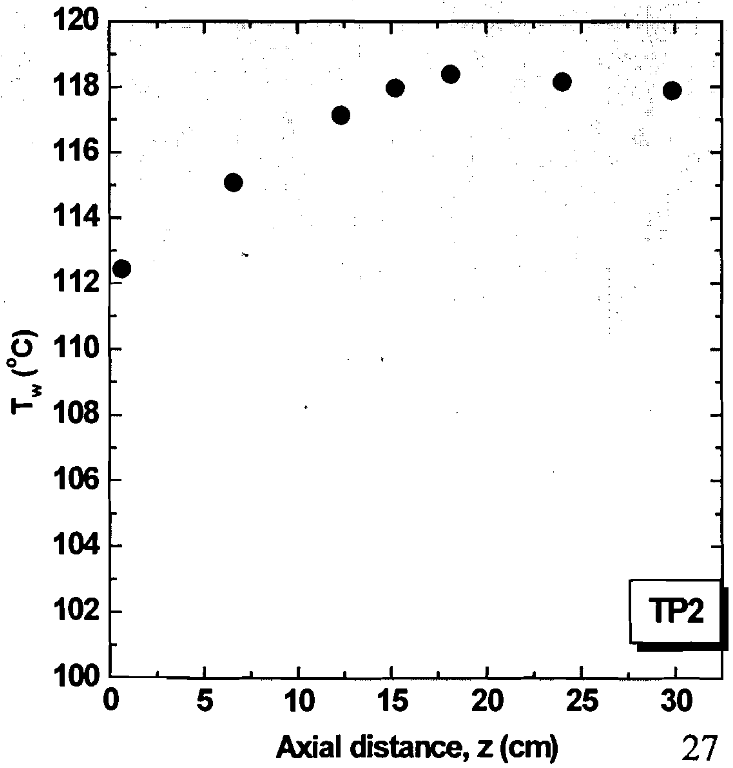
EXPERIMENTAL RESULTS

1. WALL HEAT FLUX AND WALL (q_w) FOR FLAT PLATE
2. WALL TEMPERATURE (T_w) FOR FLAT PLATE

q_w



T_w



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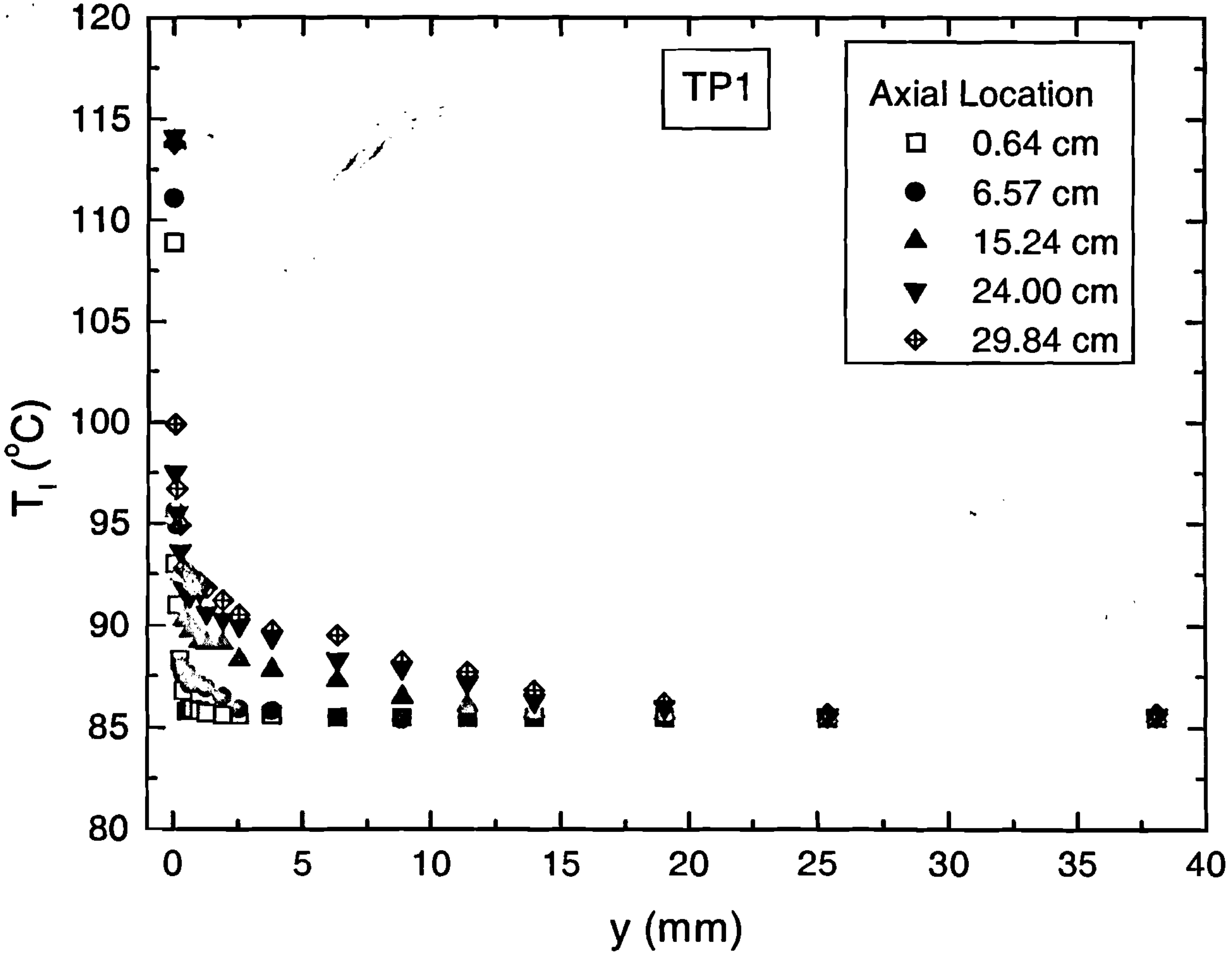
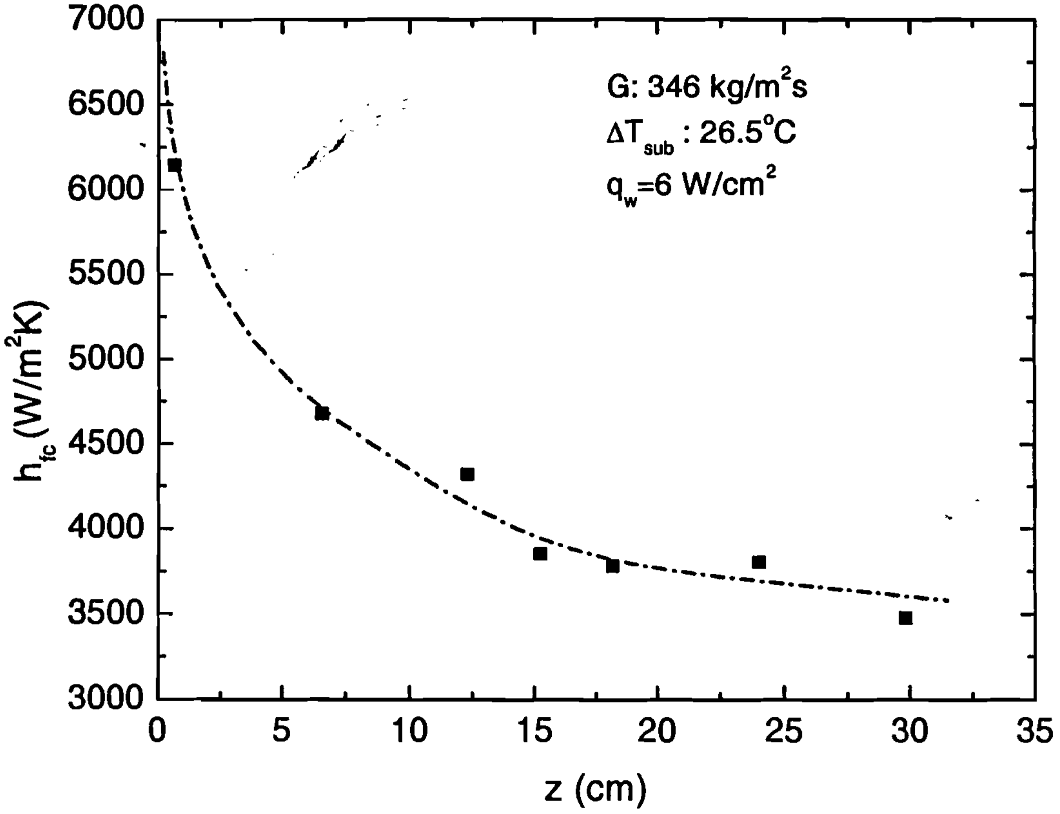
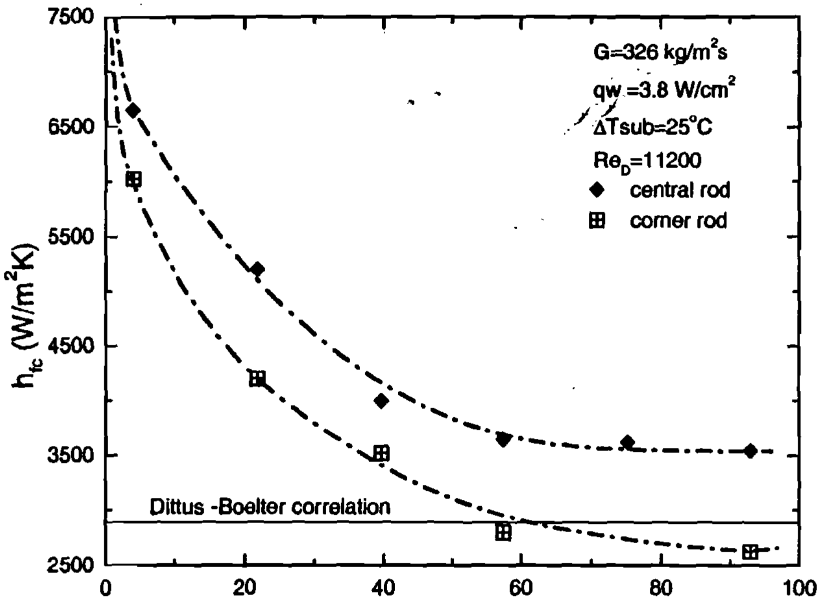
3. LIQUID TEMPERATURE PROFILE (T_l)



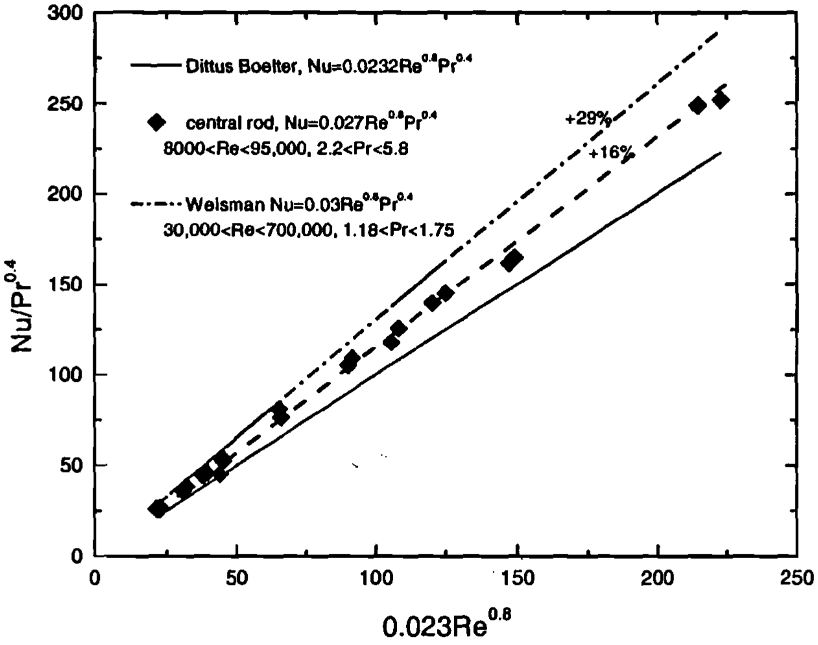
SINGLE PHASE HEAT TRANSFER FOR FLAT PLATE



SINGLE PHASE HEAT TRANSFER ROD BUNDLE



Single phase heat transfer coefficient for different rods



Comparison with correlations

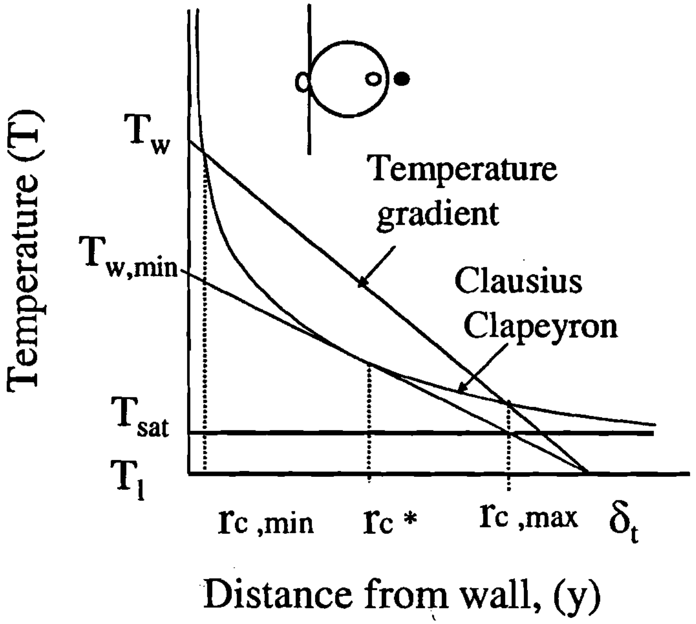
4. ONSET OF NUCLEATE BOILING (*ONB*)

PREVIOUS WORK

- **Hsu (1962)** : criteria for bubble growth

$$T - T_{sat} = \frac{4\sigma T_{sat}}{D\rho_v h_{fg}}$$

$$T - T_l = \left(1 - \frac{y}{\delta}\right)(T_w - T_l)$$



- **Bergles & Rohsenow (1964):**

$$q_{w,ONB} = 15.60p^{1.156}\left(T_w - T_{sat}\right)^{\left(2.3/p^{0.0234}\right)}$$

P in *psia*, $q_{w,ONB}$ in *Btu/ft²hr*, T in *°F*

- **Sato and Matsumara (1964)** analytically found an expression for $q_{w,ONB}$

- **Davis and Anderson (1966)** added the contact angle effect

$$q_{w,ONB} = \frac{k_l h_{fg} \rho_v}{8\sigma T_{sat} C_1}(T_w - T_{sat})^2 \qquad C_1 = 1 + \cos\varphi$$

4. ONSET OF NUCLEATE BOILING (contd.)

PREVIOUS WORK (contd.)

- **Hahne, Spindler & Shen (1990)** Under the assumption that cavity size is much smaller than the thermal boundary layer thickness

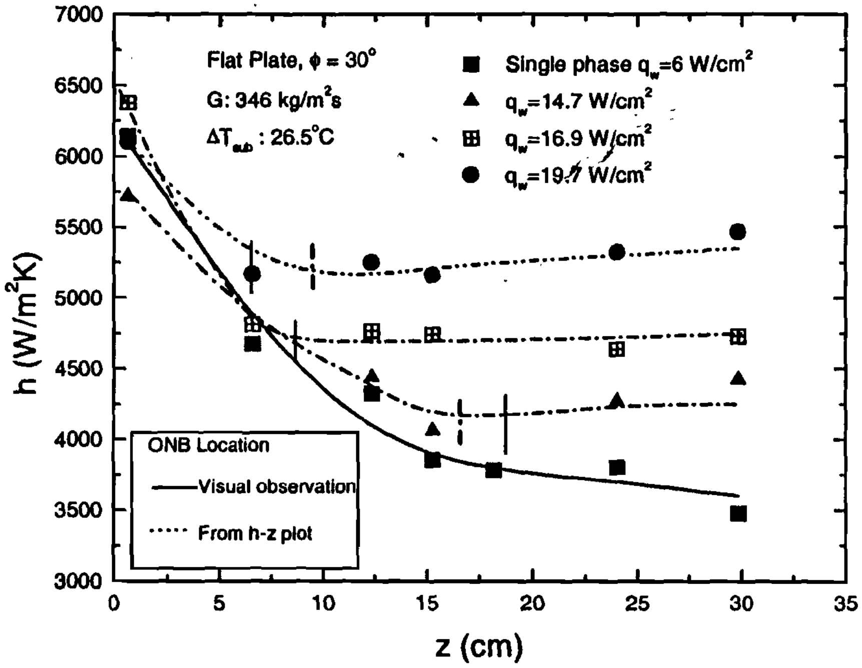
$$\Delta T_{w,ONB} = \frac{2\sigma\, T_{sat}}{r^*\,\rho_v h_{fg}} \qquad q_{w,ONB} = h_{sp}\left[\frac{2\sigma T_{sat}}{r^*\,\rho_v h_{fg}} + (\Delta T_{sub})\right]$$

where r* is found to for R12 as $\frac{2\sigma}{r^*} = 1.54 bar$

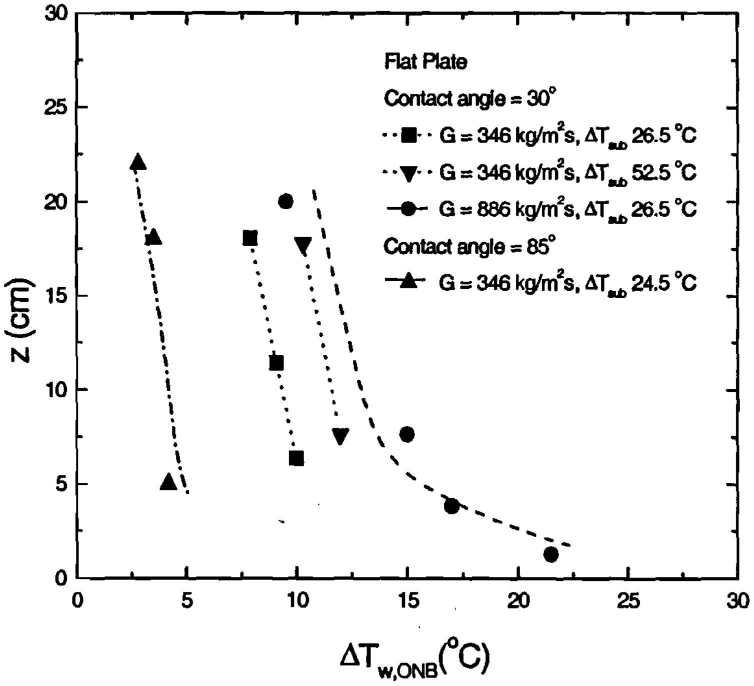
- **Kandlikar *et al.* (1997)** numerically solved the flow field to obtain the stagnation point from the wall (*y*) at $1.1 r_b$

$$\left(r_{c,min}, r_{c,max}\right) = \frac{\delta_t \sin\varphi}{2.2}\left(\frac{\Delta T_w}{\Delta T_w + \Delta T_{sub}}\right)\left[1 \mp \sqrt{1 - \frac{9.2\sigma T_{sat}(p_l)(\Delta T_w + \Delta T_{sub})}{\rho_v h_{fg}\delta_t (\Delta T_w)^2}}\right]$$

4. ONSET OF NUCLEATE BOILING (contd.)



Heat transfer coefficient as a function of axial distance for different heat fluxes (G = 346 *kg/m*^{2}s $\Delta T_{sub,in}$ 26.5 °C).



Variation of ONB location with $\Delta T_{w,ONB}$ for various flow rates, liquid subcoolings, and contact angles.

4. ONSET OF NUCLEATE BOILING (contd.)

PRESENT STUDY (New correlation)

$$D_c = D_c^* f(\phi)$$

-D_c is the corrected cavity diameter

$$D_c^* = \left[\frac{8\sigma T_{sat} k_l}{\rho_v h_{fg} q_w}\right]^{\frac{1}{2}}$$

-D_c^* is the cavity size corresponding to Hsu's minimum wall superheat

$$\Delta T_{w,ONB} = T_{sat}(P_v) - T_{sat}(P_l)$$

-where $P_v - P_l = \dfrac{4\sigma}{D_c}$

$$\Delta T_{w,ONB} = \frac{4\sigma}{D_c}\frac{T_{sat}(P_l)}{\rho_v h_{fg}}$$

-For small superheats

$$q_{w,ONB} = h_{sp}(z)\Delta T_{w,ONB} + h_{sp}(z)\,(T_{sat} - T_l)$$

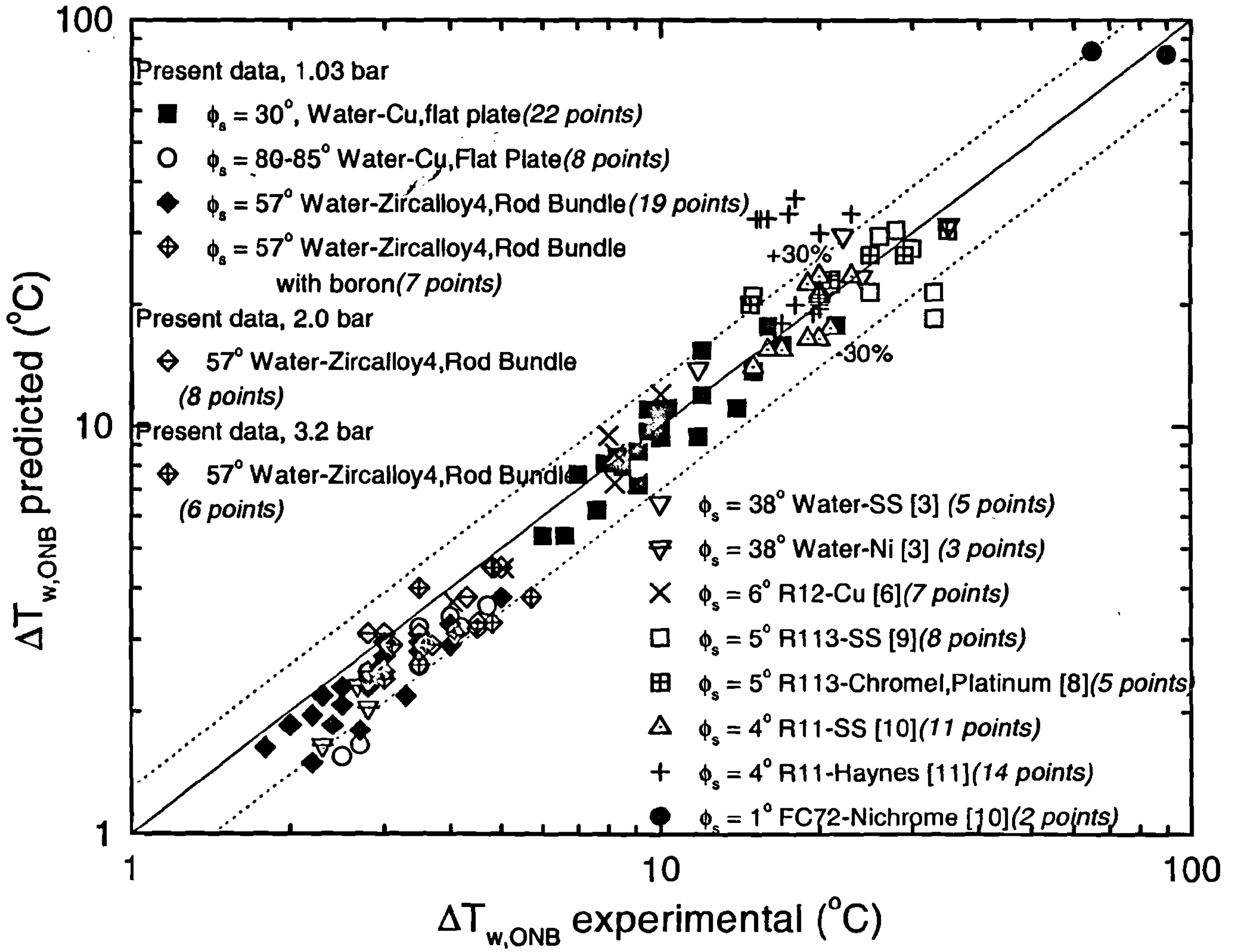
$$f = 1 - \exp(-\phi^3 - 0.5\phi)$$

-From experimental data

-ϕ in radians

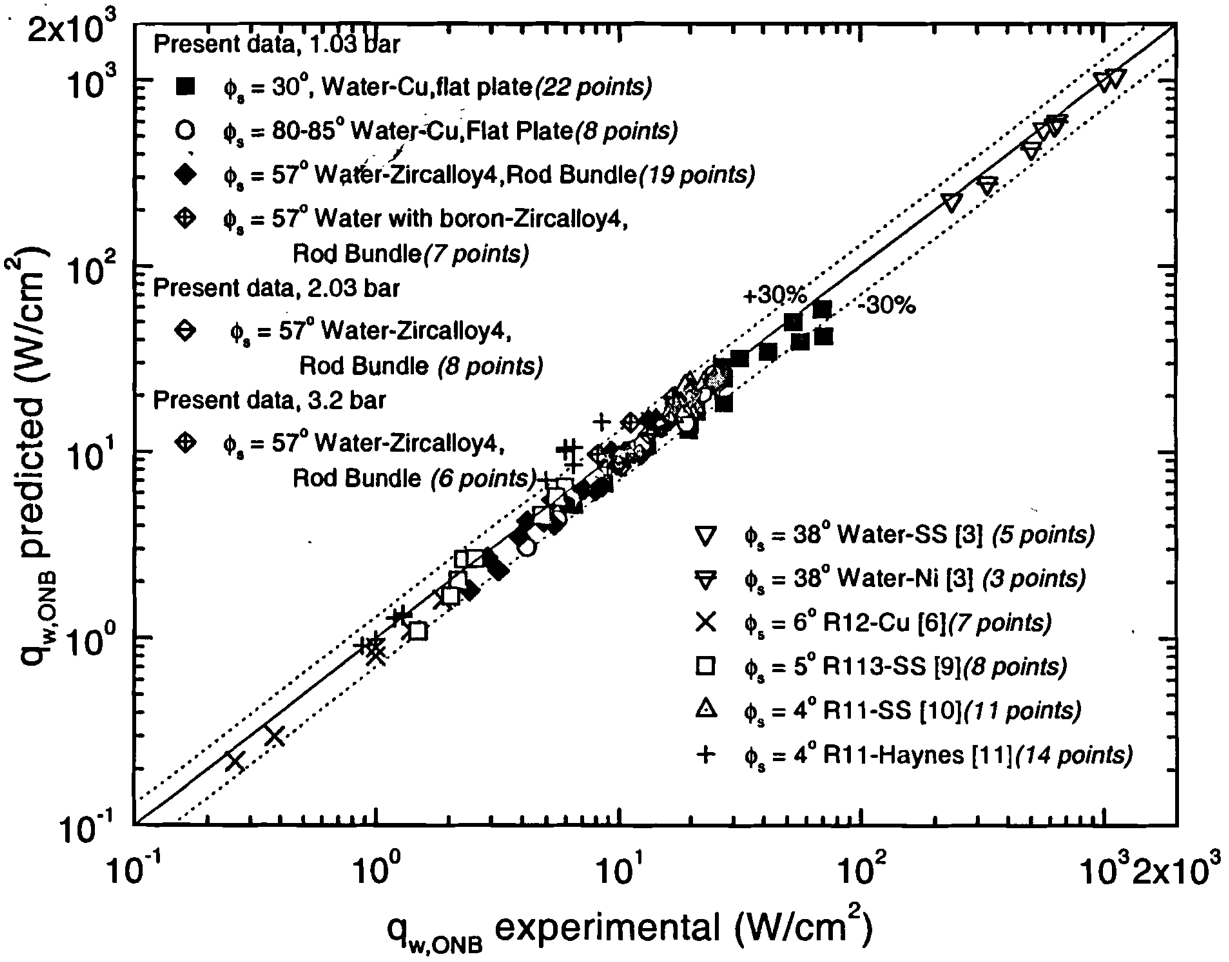
4. ONSET OF NUCLEATE BOILING (contd.)

PRESENT STUDY



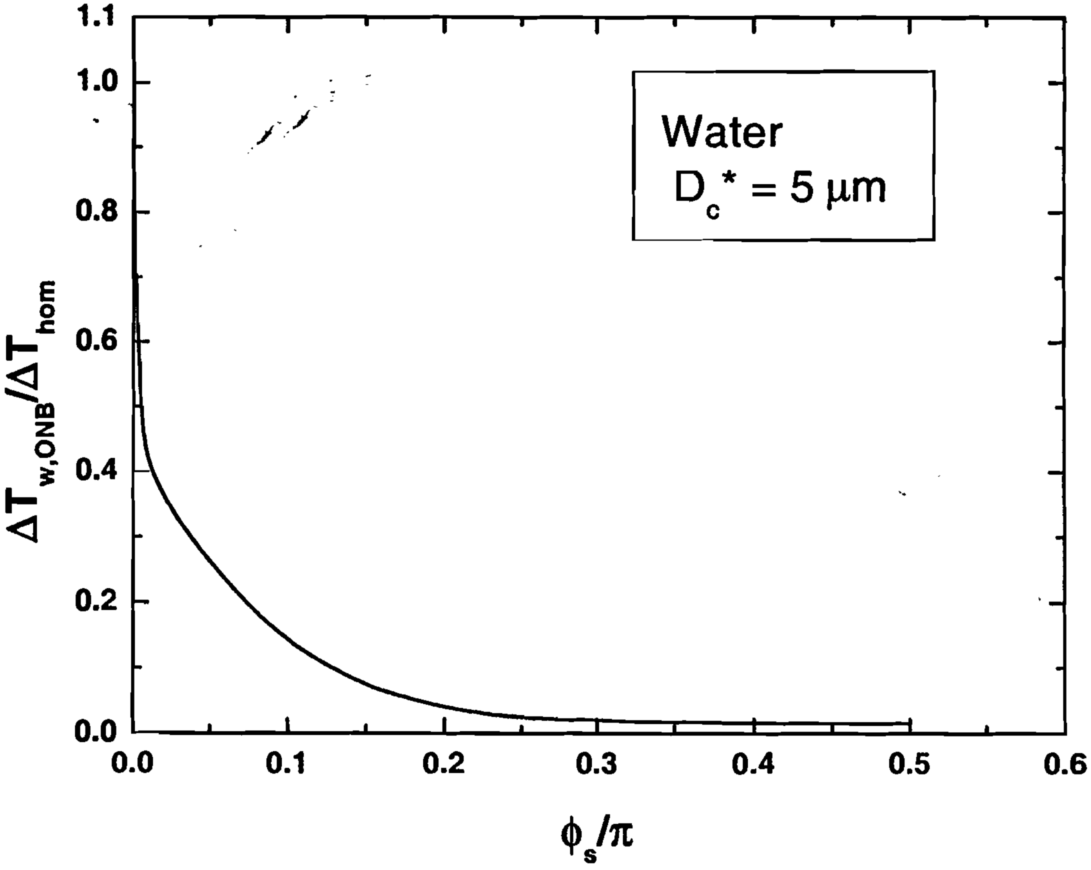
4. ONSET OF NUCLEATE BOILING (contd.)

PRESENT STUDY



4. ONSET OF NUCLEATE BOILING (contd.)

PRESENT STUDY



Variation of $\Delta T_{w,ONB}$ with ϕ

5. NUCLEATION SITE DENSITY (N_a)

PREVIOUS WORK

Kocamustafaogullari & Ishii (1983):

$$N_a^* = R_c^{*-4.4} f(\rho^*)$$

$$R_c^* = \frac{R_c}{(D_d/2)}, \quad R_c = \left(2\sigma\left[1+\rho_g/\rho_f\right]/P_f\right)\left(\exp\left[h_{fg}\left(T_g - T_{sat}\right)/\left(RT_g T_{sat}\right)\right]-1\right)$$

$$f(\rho^*) = 2.157\times10^{-7}\rho^{*-3.2}\left(1+0.0049\rho^*\right)^{4.13}$$

$$N_a^* = N_a\left(D_d^2\right), \quad \rho^* = \frac{\rho_f - \rho_g}{\rho_g}, \quad D_d = 2.496\text{x}10^{-5}\left(\frac{\rho_f - \rho_g}{\rho_g}\right)^{0.9}\phi\sqrt{\frac{\sigma}{g\left(\rho_f - \rho_g\right)}}$$

Wang & Dhir (1993):

$$N_a = 5.0\times10^5\left(1-\cos\phi\right)D_c^{-6.0}$$

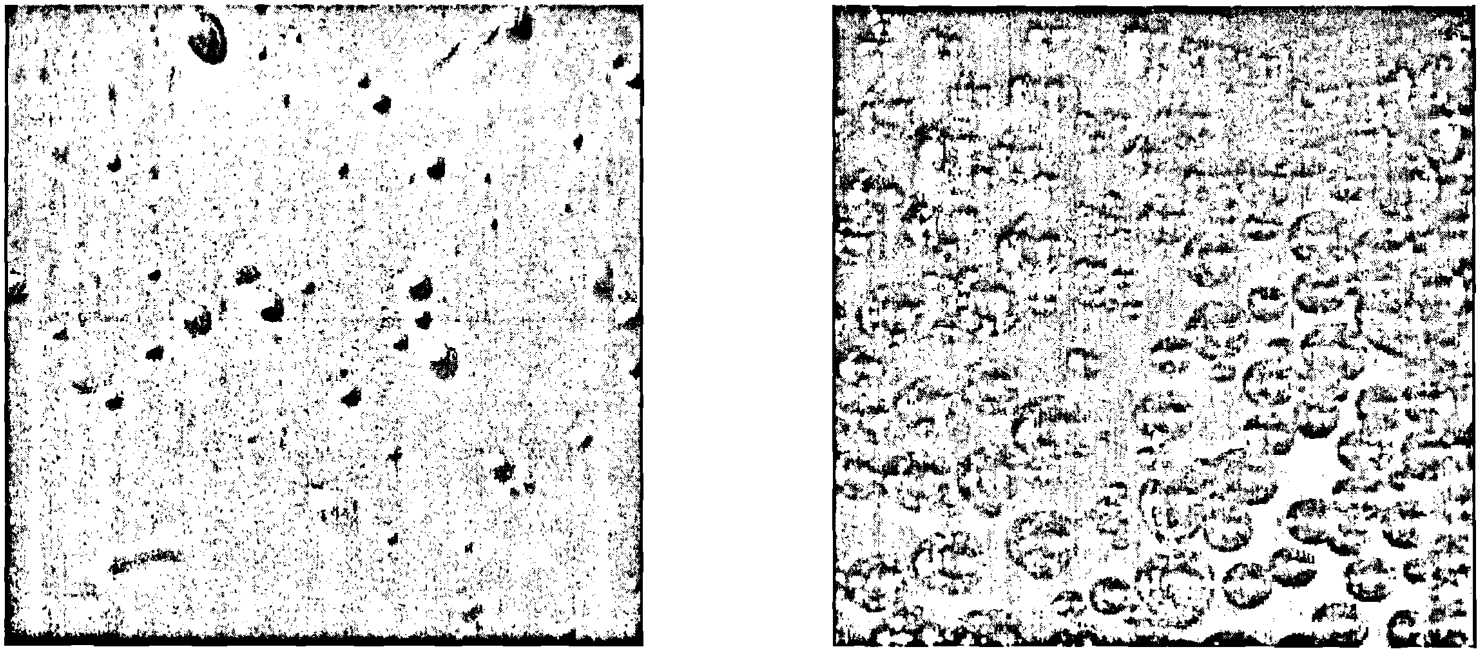
Valid for Dc<5.8 μm

$$D_c = \frac{4\sigma T_{sat}}{\rho_v h_{fg}\Delta T_w}$$

5. NUCLEATION SITE DENSITY (contd.)

PRESENT STUDY

Effect of contact angle (ϕ) on N_a



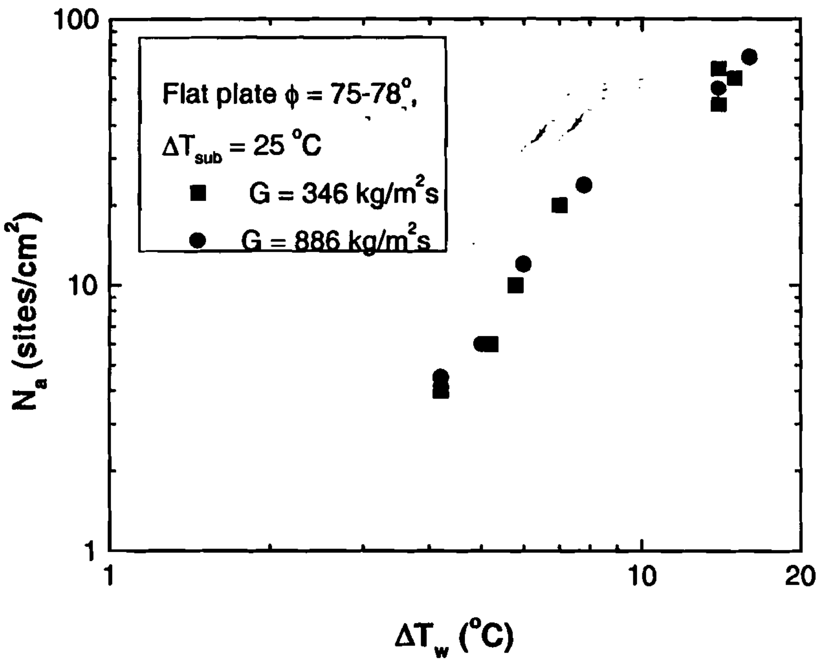
$\phi = 30^{\circ}$, $\Delta T_w = 7.2\ ^{\circ}C$

$\phi = 90^{\circ}$, $\Delta T_w = 7.4\ ^{\circ}C$

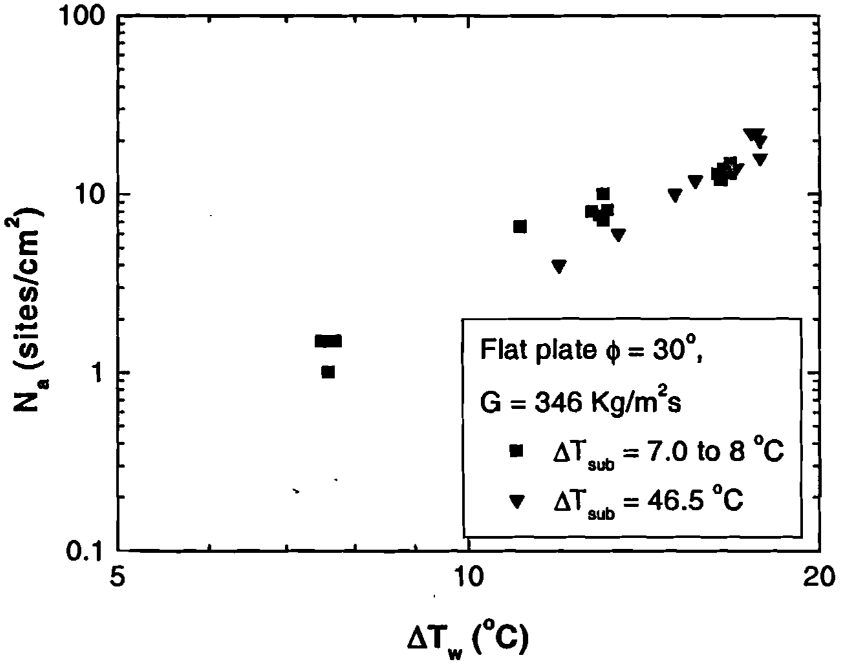
- For given ΔT_w, N_a increases with increasing ϕ

5. NUCLEATION SITE DENSITY (contd.)

PRESENT STUDY



Comparison of N_a for two different mass fluxes.



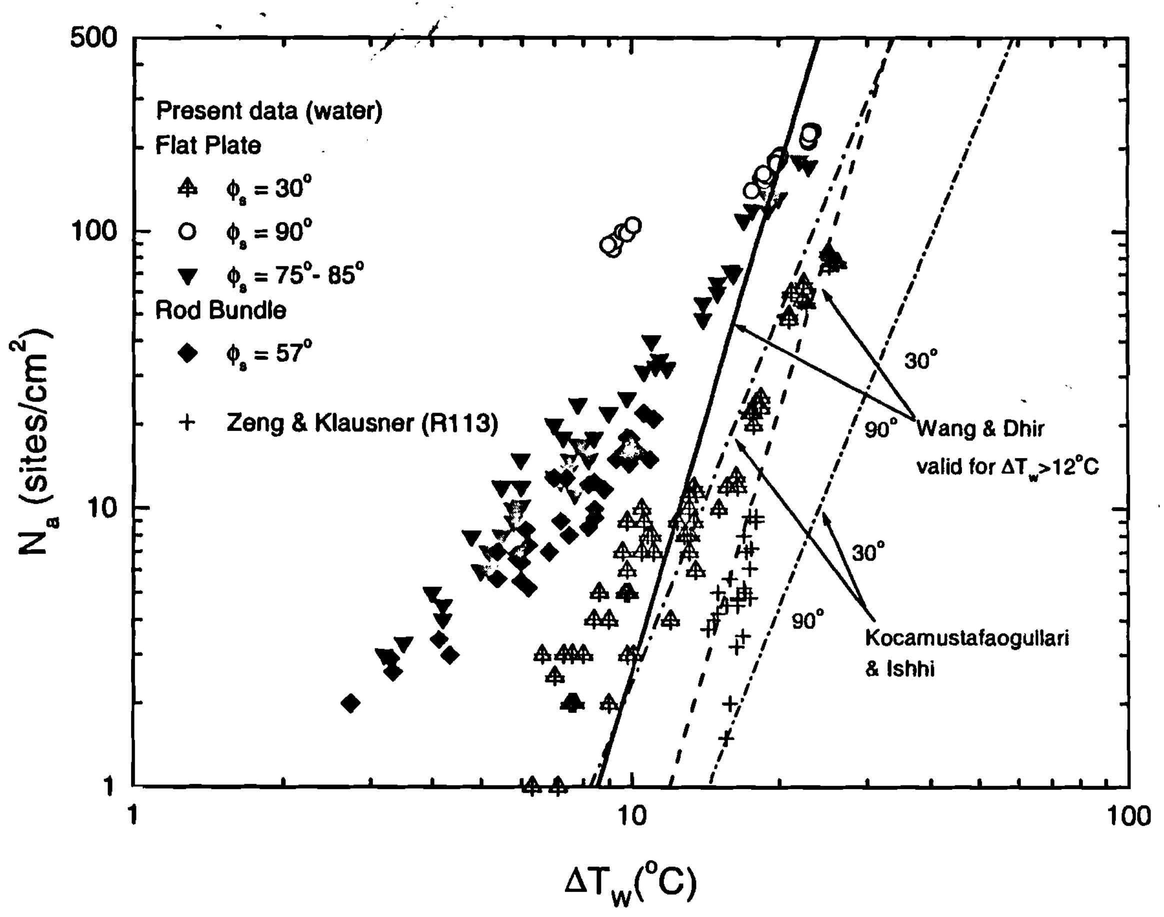
Comparison of N_a for different liquid subcoolings.

5. NUCLEATION SITE DENSITY (contd.)

PRESENT STUDY: **(New correlation)**

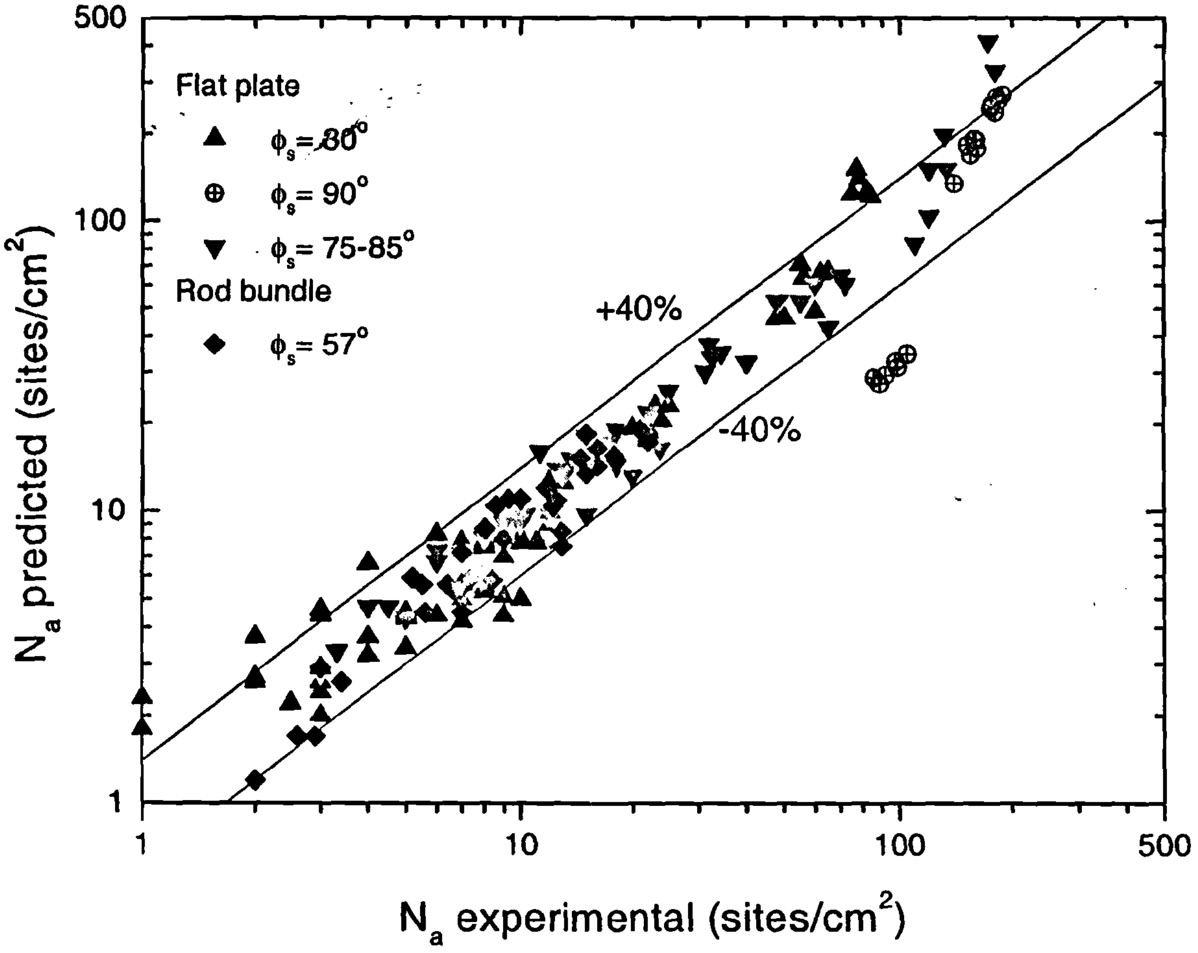
For $\Delta T_w < 15^o C$ $N_a = 0.34(1-\cos\phi)\Delta T_w^{2.0}$ sites/cm^2

For $\Delta T_w \geq 15^o C$ $N_a = 3.4x10^{-5}(1-\cos\phi)\Delta T_w^{5.3}$ sites/cm^2

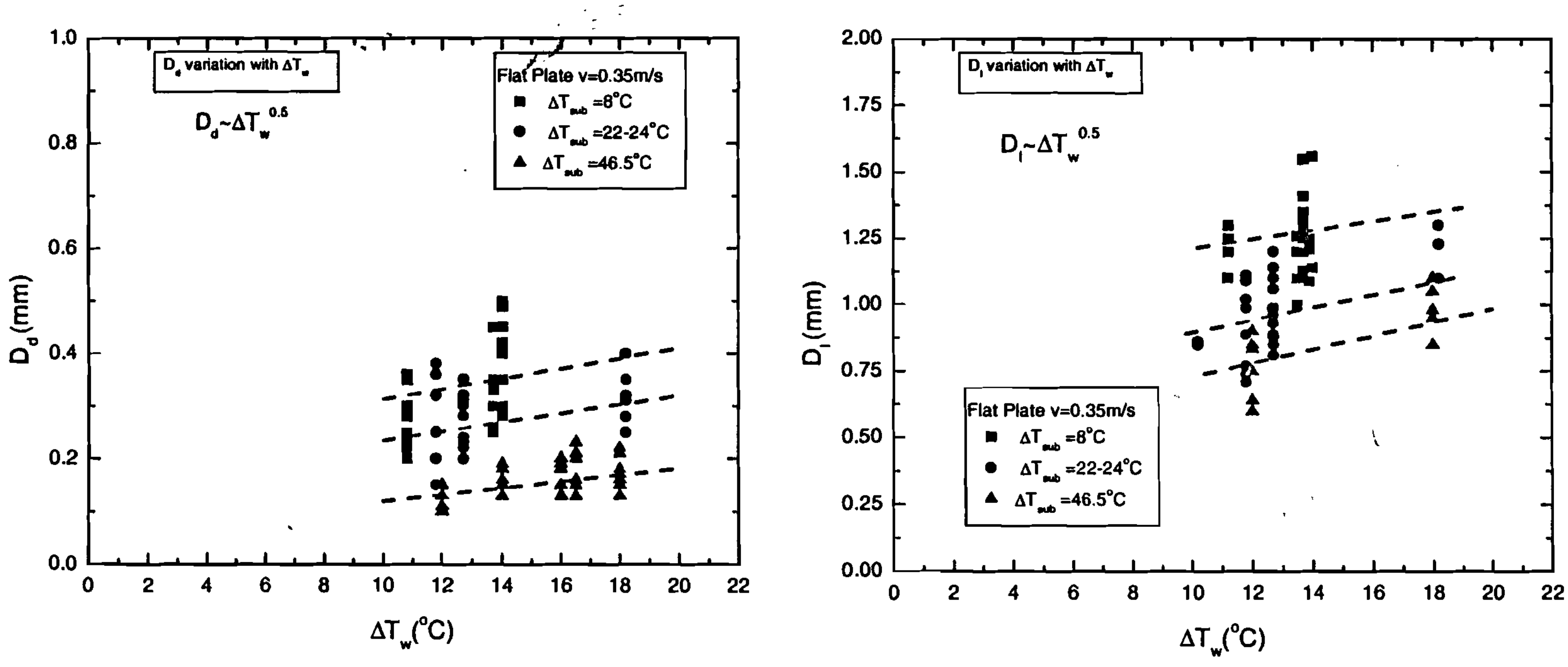


5. NUCLEATION SITE DENSITY (contd.)

Comparison of predicted values with experimental values



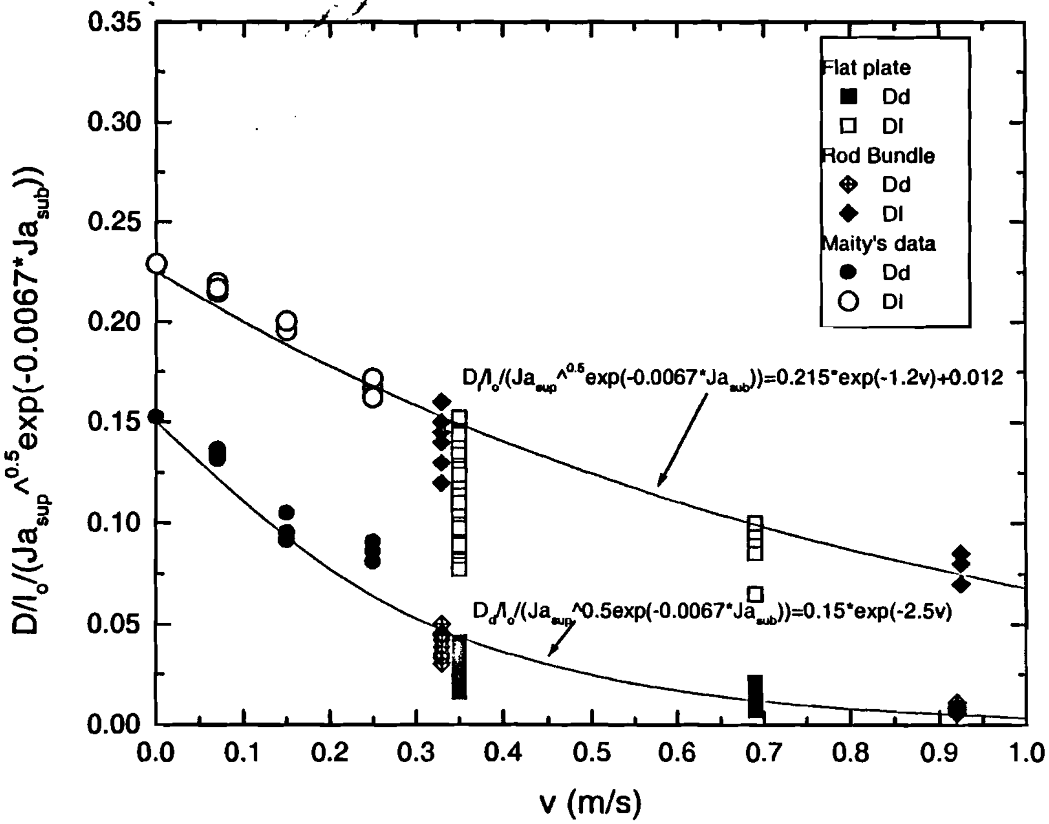
6. BUBBLE DEPARTURE, D_d AND LIFT-OFF DIAMETER, D_l



Variation of D_d, D_l with ΔT_w and ΔT_{sub}

6. BUBBLE DEPARTURE, D_d AND LIFT-OFF DIAMETER, D_l (contd.)

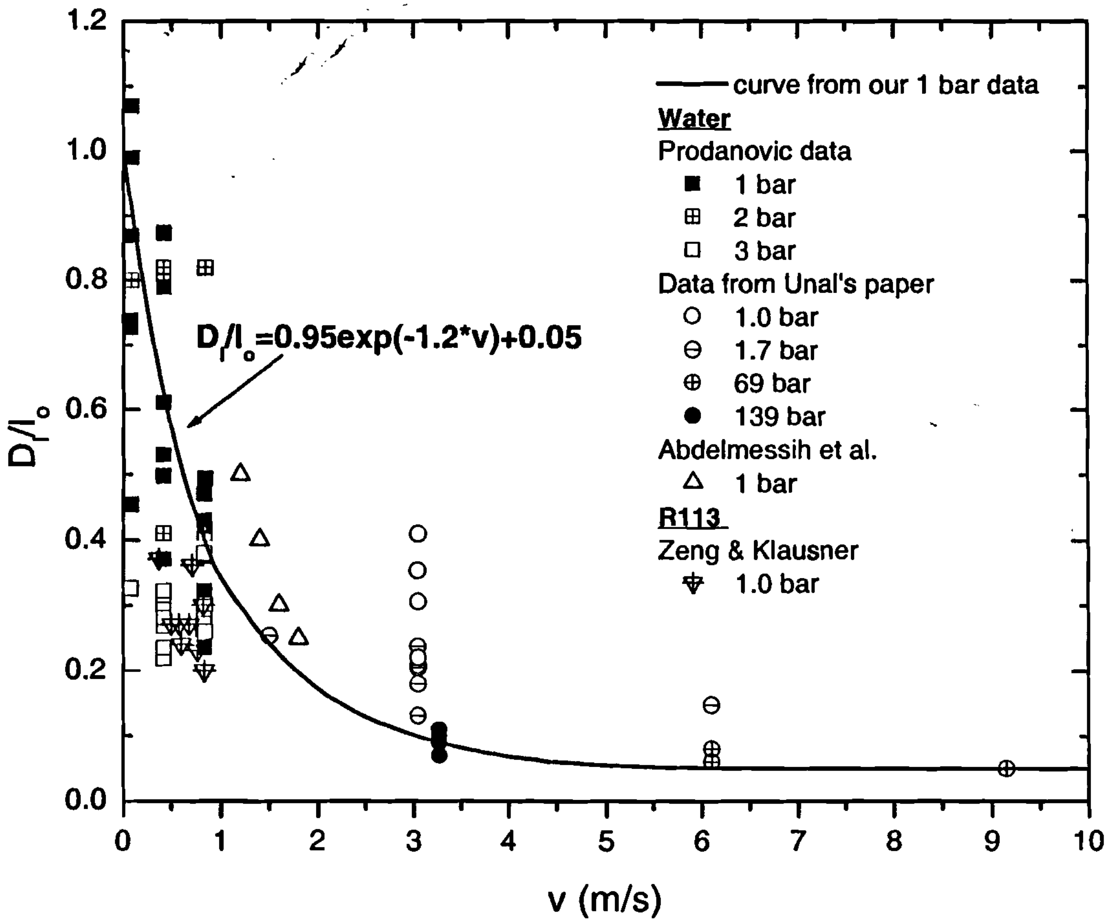
$$l_o = \sqrt{\frac{\sigma}{g\,(\rho_l - \rho_v)}} \qquad Ja_{sup} = \frac{\rho_l Cp_l \Delta T_w}{\rho_v h_{fg}} \qquad Ja_{sub} = \frac{\rho_l Cp_l \Delta T_{sub}}{\rho_v h_{fg}}$$



Variation of D_d, D_l with v, ΔT_w and ΔT_{sub}

6. BUBBLE DEPARTURE, D_d AND LIFT-OFF DIAMETER, D_l (contd.)

Lift off diameter information available in literature with present correlation, as a function of velocity only



7. ONSET OF SIGNIFICANT VOIDS (*OSV*)

PREVIOUS WORK

Bowring (1962):

$$\Delta T_{sub,OSV} = q_w(14+0.1P)/U_l,\ \Delta T_{sub,OSV} - {}^oC,\ q_w - W/cm^2,\ P - atm.,\ U_l - cm/s$$

Levy (1967):

$$\Delta T_{sub,OSV} = q_w\left[\frac{1}{h_{sp}} - \frac{T_b^+}{\rho_l c_{pl}\sqrt{\tau_w/\rho_l}}\right],\ T_b^+ = f\left(Pr, Y_b^+\right) = turbulent\ temperarture\ profile$$

Dix (1971):

$$\Delta T_{sub,OSV} = 0.00135 Re^{0.5}\left(q_w/h_{sp}\right)$$

Saha & Zuber (1974):

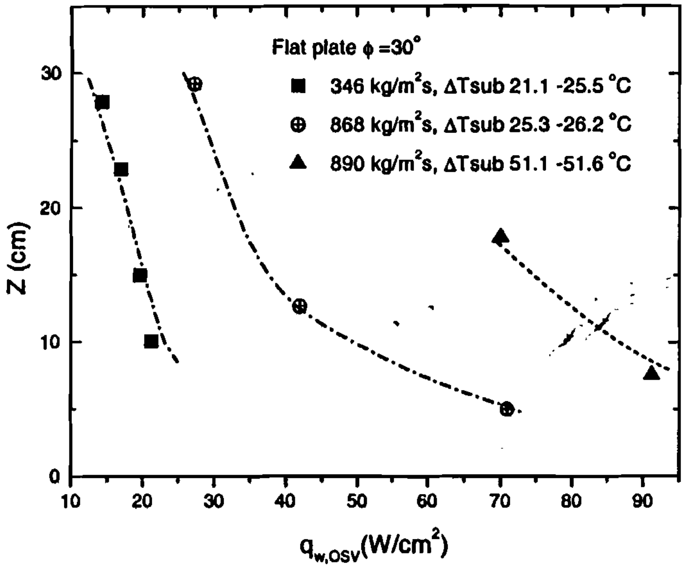
$$Nu = 455 = \frac{q_w D_h}{k_l \Delta T_{sub,OSV}} \quad Pe \le 70{,}000$$

$$St = 0.0065 = \frac{q_w}{G c_p \Delta T_{sub,OSV}} \quad Pe \ge 70{,}000$$

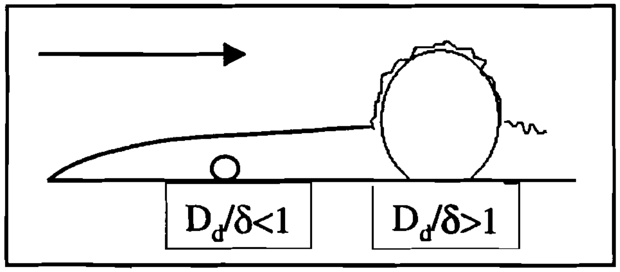
Zeitoun *et al.* (1994):

$$\frac{q_w D_s}{k_l \Delta T_{sub,OSV}} = Re_b^{0.6} Pr^{1/3},\quad D_s = \frac{0.0683\left(\rho_l/\rho_g\right)^{1.326}\sqrt{\sigma/g\Delta\rho}}{Re^{0.324}\left(Ja + \dfrac{149.2\left(\rho_l/\rho_g\right)^{1.326}}{Bo^{0.487} Re^{1.6}}\right)}$$

7. ONSET OF SIGNIFICANT VOIDS (contd.)



Axial variation of OSV location with wall heat flux for various flow rates and liquid subcooling



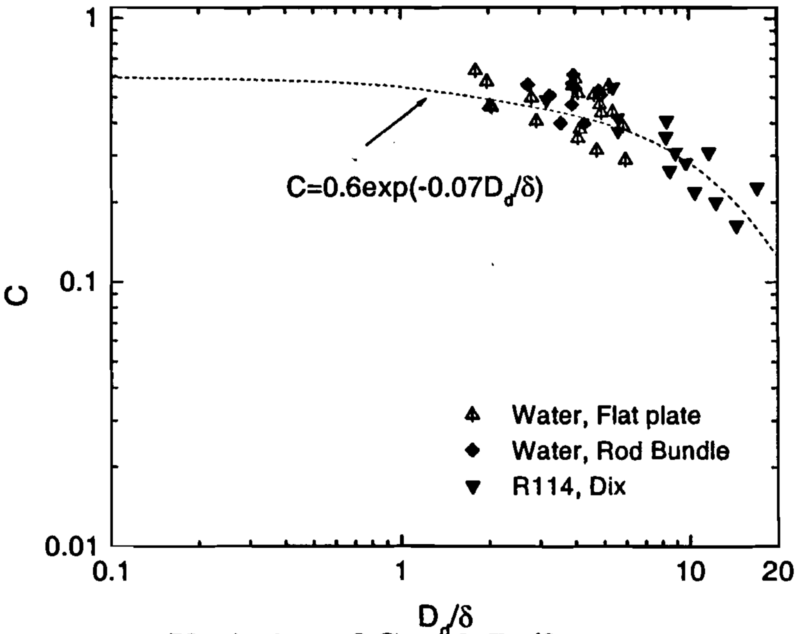
Proposed correlation for OSV

$$\frac{\Delta T_{sub,OSV}\, h_{fc}}{q_w} = C$$

Where **C** is an empirical constant, $f(D_d/\delta)$ $[\delta = k/h_{fc}]$

-decreases with increase of D_d/δ and vice-versa

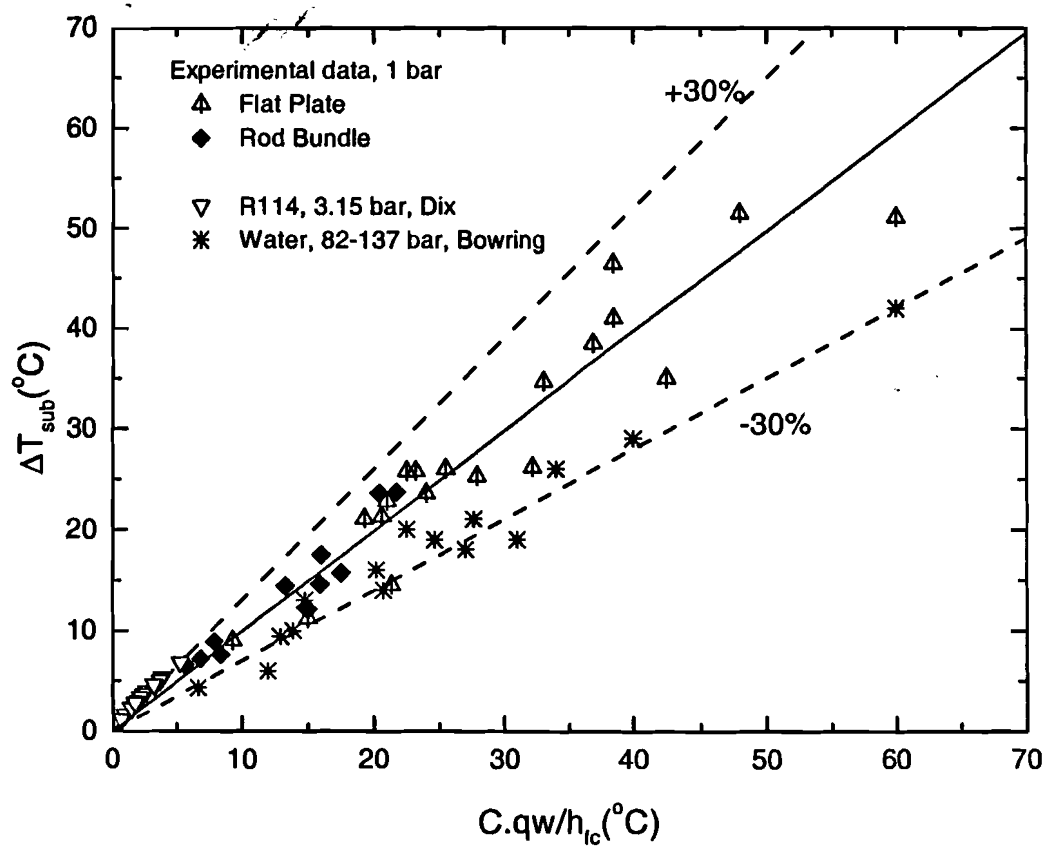
-For thicker thermal layer bubble will be surrounded by superheated liquid, whereas for thinner thermal layer bubble will be exposed to subcooled liquid



Variation of C with D_d/δ

7. ONSET OF SIGNIFICANT VOIDS (contd.)

Comparison of proposed correlations with data from present work& some data available in the literature

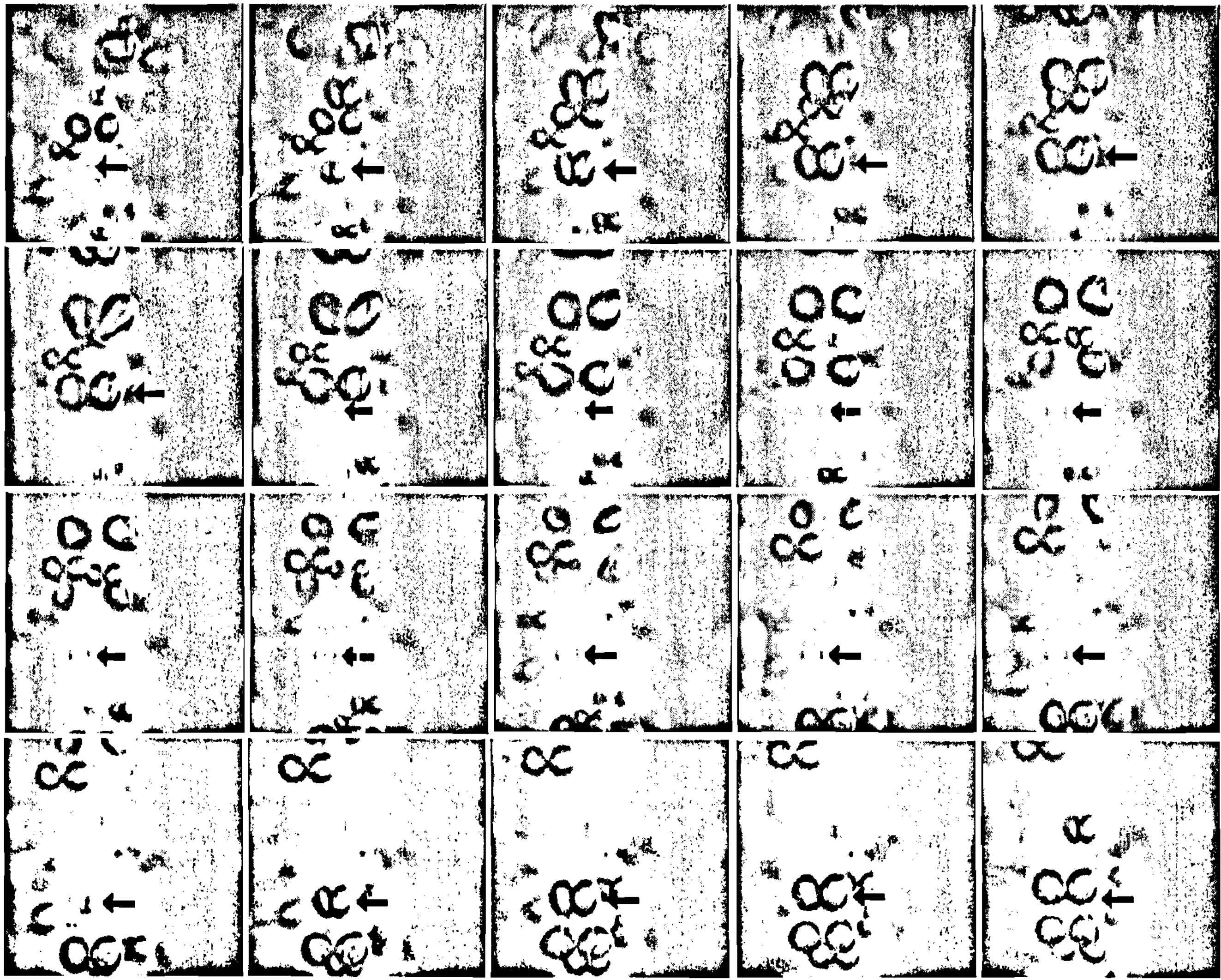


8. BUBBLE RELEASE FREQUENCY (*f*)

Bubble release sequence

Sequence: left to right and top to bottom

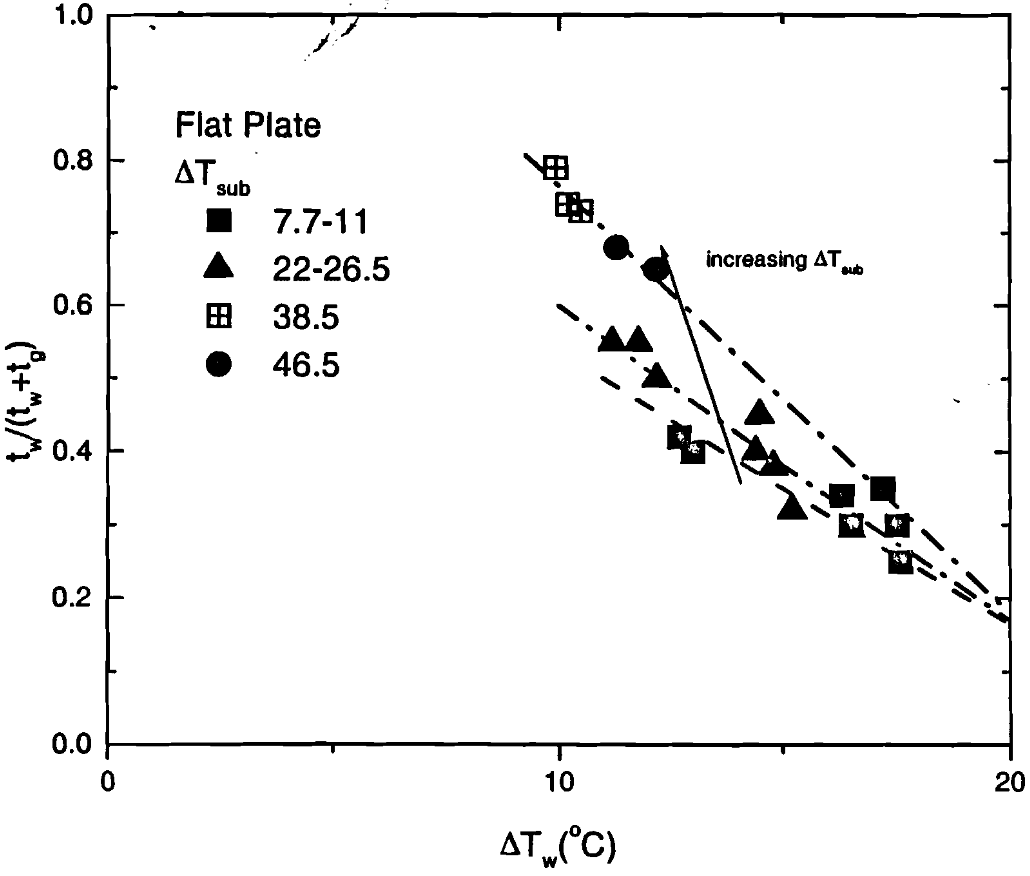
Time interval between frames is 0.8 ms



8. BUBBLE RELEASE FREQUENCY (contd.)

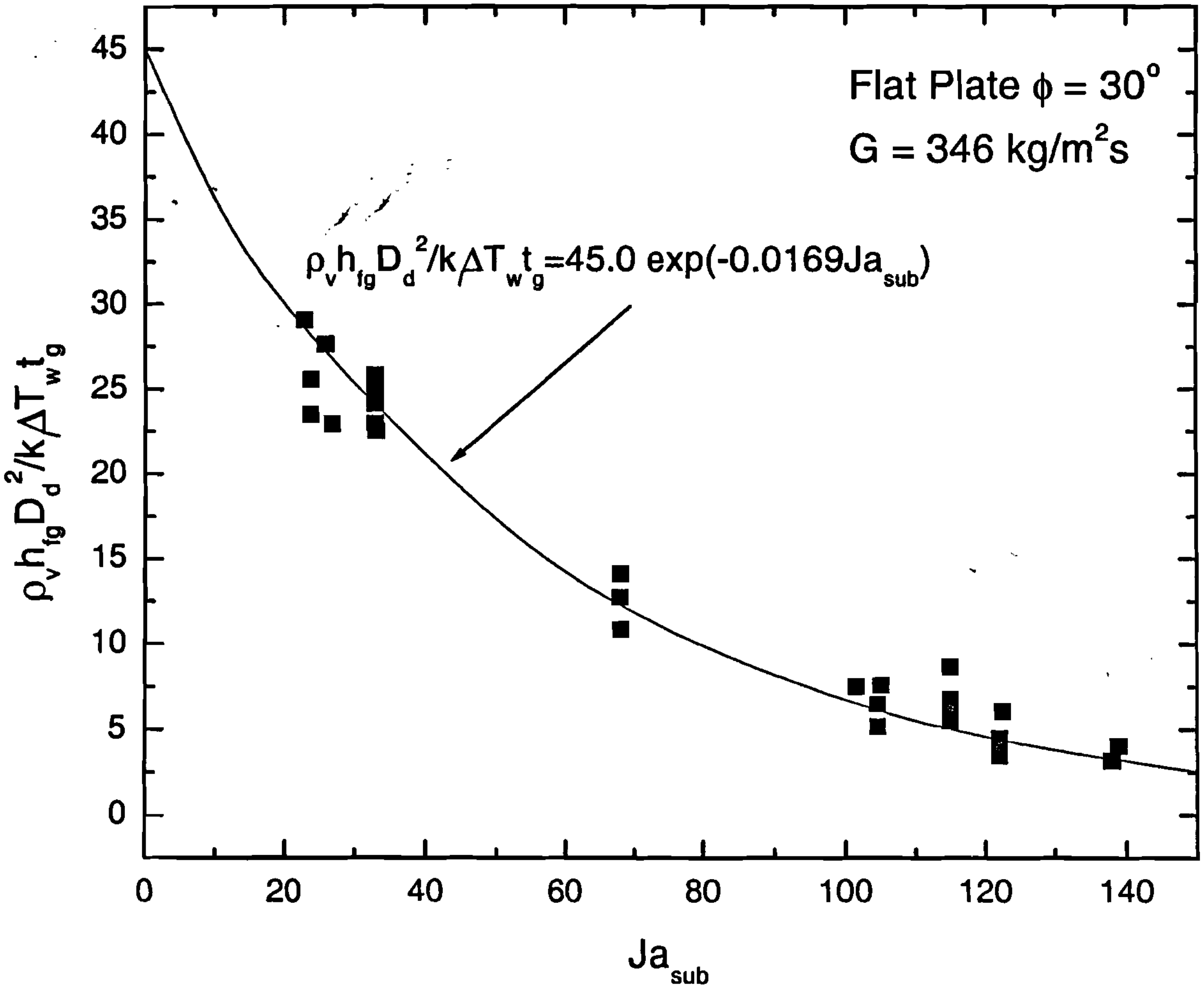
$$f = 1/(t_w + t_g)$$

Waiting time ratio $[t_w/(t_w+t_g)]$ as a function of ΔT_w



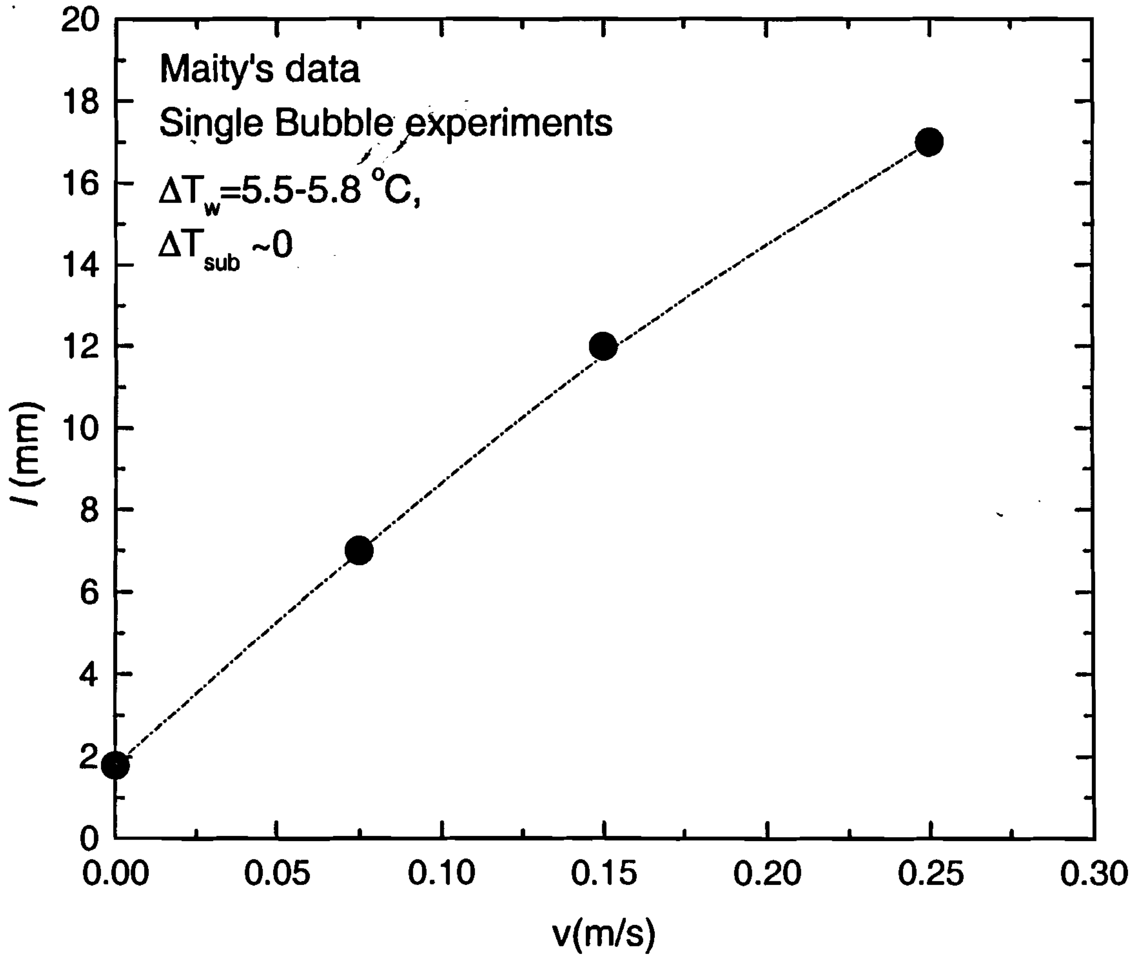
8. BUBBLE RELEASE FREQUENCY (contd.)

Growth time (t_g) varying with D_d, ΔT_w and ΔT_{sub}



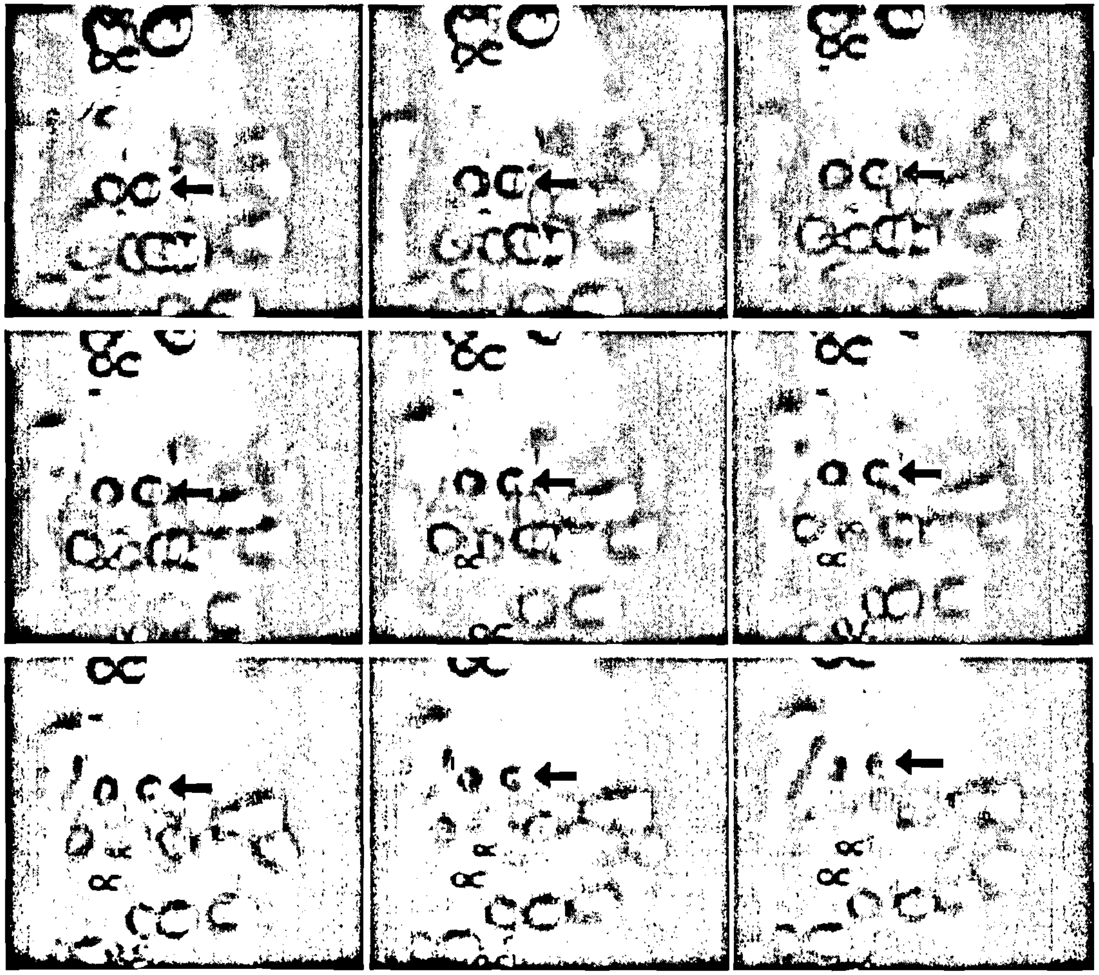
9. BUBBLE SLIDING DISTANCE (*l*)

Sliding distance varying with velocity



10. CONDENSATION HEAT TRANSFER COEFFICIENT - DETACHED BUBBLES

Bubble collapse sequence



Sequence: left to right and top to bottom

Time interval between frames is 0.8 ms

10. CONDENSATION HEAT TRANSFER COEFFICIENT - DETACHED BUBBLES (contd.)

PREVIOUS WORK

Isenberg & Sideman (1970):

$$\beta = \left(1 - \frac{3}{\pi^{1/2}} Re_{bo}^{1/2} Pr^{1/3} Ja Fo_o\right)^{2/3}, \qquad Nu_c = \frac{1}{\pi^{1/2}} Re_b^{1/2} Pr^{1/3}$$

Chen & Mayinger (1992):

$$\beta = \left(1 - 0.56 Re_{bo}^{0.7} Pr^{0.5} Ja Fo_o\right)^{0.9}, \qquad Nu_c = 0.185 Re_b^{0.7} Pr^{0.5}$$

Zeitoun *et. al* (1995):

$$\beta = \left(1 - 5.67 Re_{bo}^{0.61} \alpha^{0.328} Ja^{0.629} Fo_o\right)^{0.72}, \qquad Nu_c = 2.04 Re_b^{0.61} \alpha^{0.328} Pr^{-0.308}$$

$$\beta = D_b / D_{bo}, \; Nu_c = \frac{h_c D_b}{k_l}$$

α = void fraction

$$Pr = \frac{\mu_l c_{p,l}}{k_l}, \quad Re_b = \frac{\rho_l U_{b,rel} D_b}{\mu_l}, \quad Re_{bo} = \frac{\rho_l U_{b,rel} D_{bo}}{\mu_l}$$

$$Ja = \frac{\rho_l c_{p,l} \Delta T_{sub}}{\rho_v h_{fg}}, \quad Fo_o = \frac{(k_l / \rho_l c_{p,l})t}{D_{bo}^2}$$

10. CONDENSATION HEAT TRANSFER COEFFICIENT - DETACHED BUBBLES (contd.)

PRESENT STUDY

Energy balance around a collapsing vapor bubble yields $h_c = \frac{\rho_v h_{fg}}{2\Delta T_{sub}}\left(\frac{dD_b}{dt}\right)$

Bubble velocity and rate of change in bubble diameter calculated from the rate of change of bubble position and diameter.

Local liquid subcooled calculated from measured liquid temperature profile

Correlation of data yields,

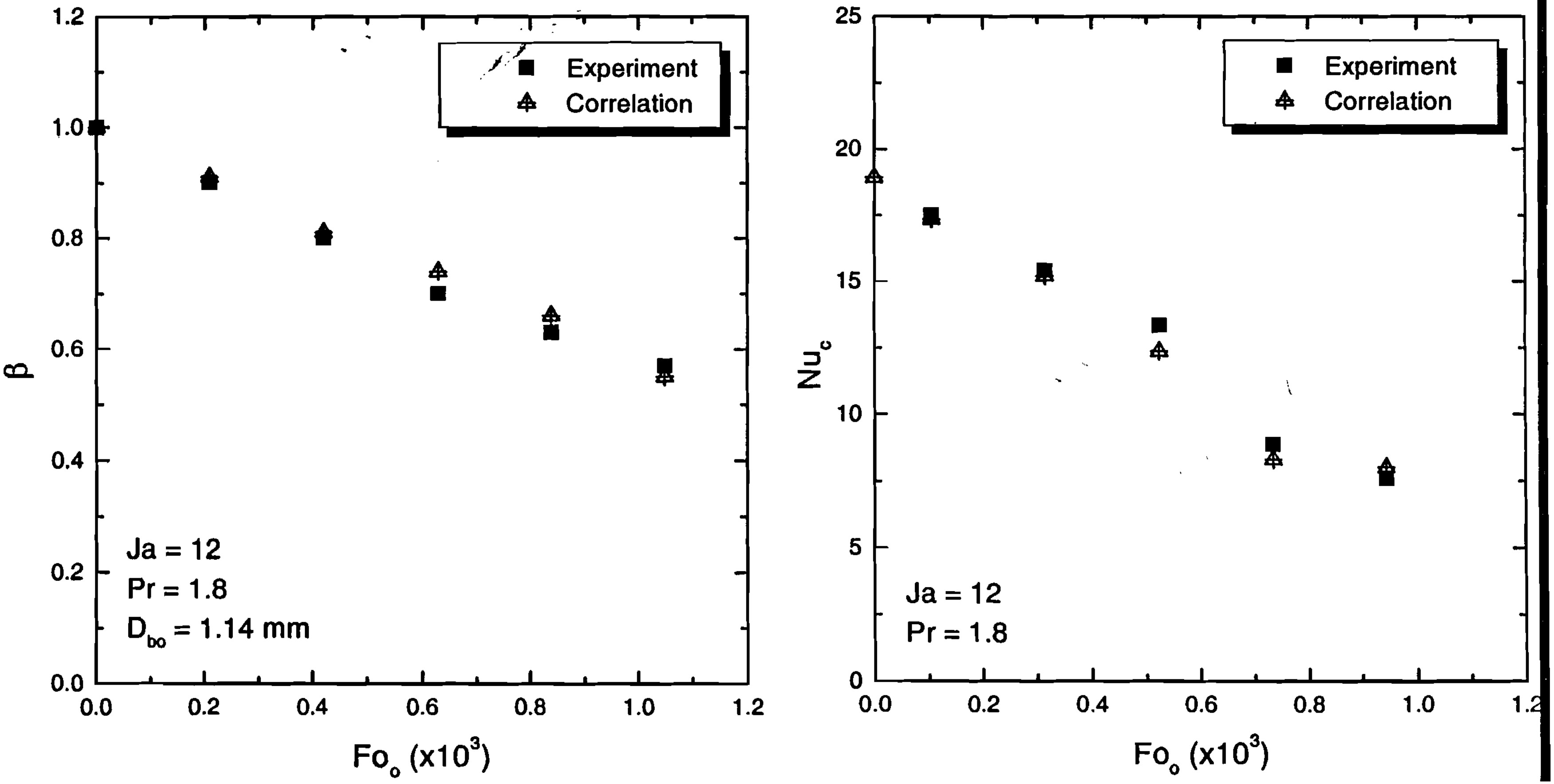
$\beta^{3/2} = 1 - 1.8 Re_{bo}^{1/2} Pr^{1/3} Ja Fo_o \left(1 - 0.72 Ja^{9/10} Fo_o^{\ 2/3}\right)$, $\quad Nu_c = 0.6 Re_b^{1/2} Pr^{1/3} \left(1 - 1.20 Ja^{9/10} Fo_o^{\ 2/3}\right)$

Range: $20 < Re_b < 700$, $1.8 < Pr < 2.8$, $12 < Ja < 100$

These correlations correctly capture the physics involved. In the Nu_c correlation, forced convection around a solid sphere is accounted for by the $0.6 Re_b^{1/2} Pr^{1/3}$ term, while the thickening of thermal boundary layer is accounted for by the $\left(1 - 1.20 Ja^{9/10} Fo_o^{\ 2/3}\right)$ term.

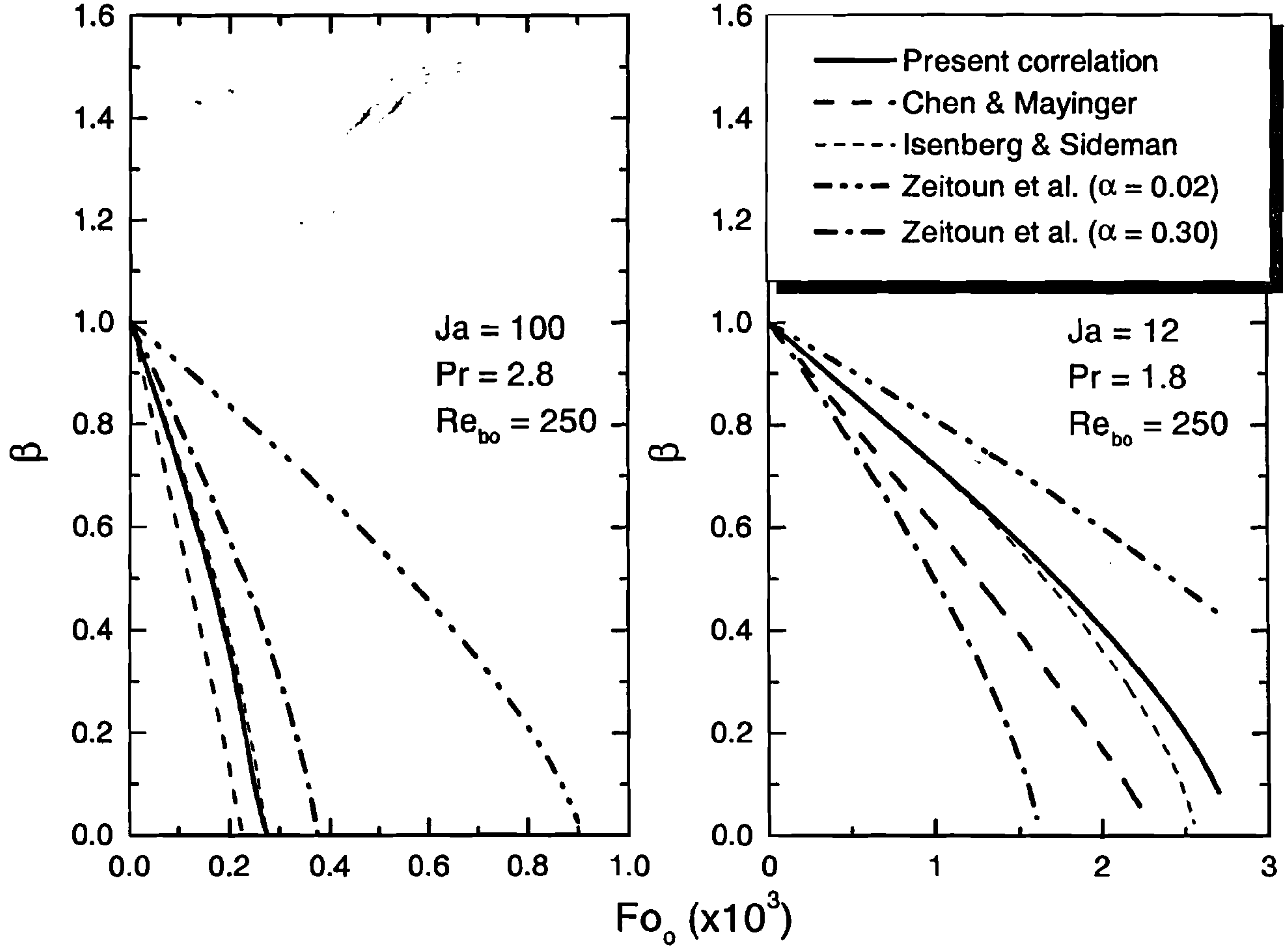
10. CONDENSATION HEAT TRANSFER COEFFICIENT - DETACHED BUBBLES (contd.)

Comparison of experimental data with correlation



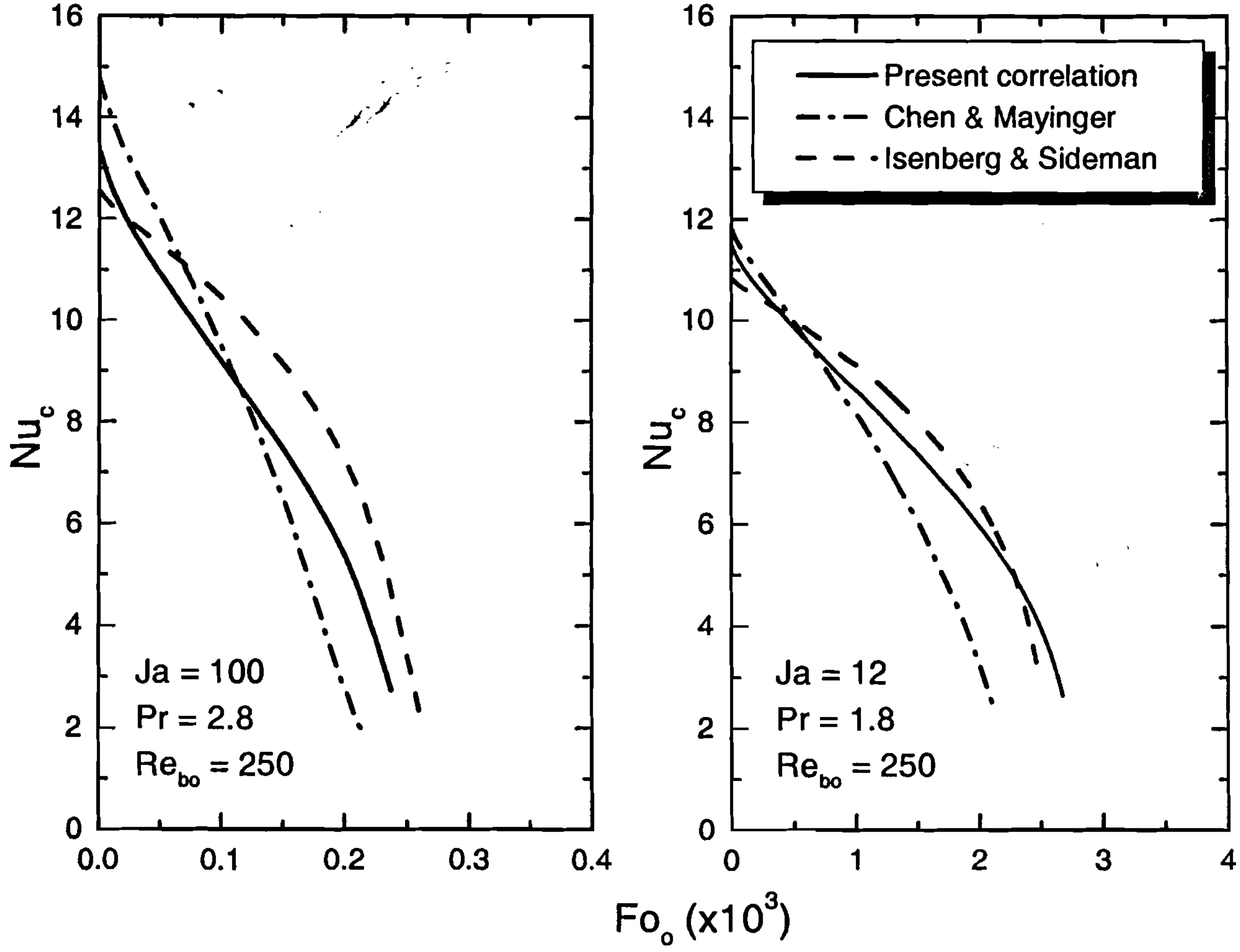
10. CONDENSATION HEAT TRANSFER COEFFICIENT - DETACHED BUBBLES (contd.)

Comparison of β correlations



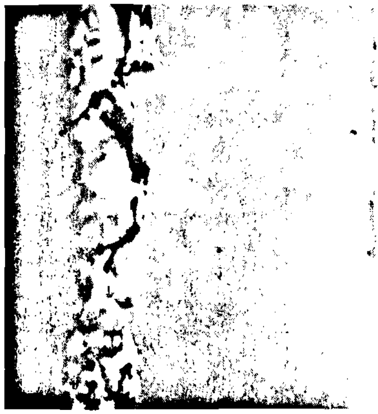
10. CONDENSATION HEAT TRANSFER COEFFICIENT - DETACHED BUBBLES (contd.)

Comparison of Nu_c correlations

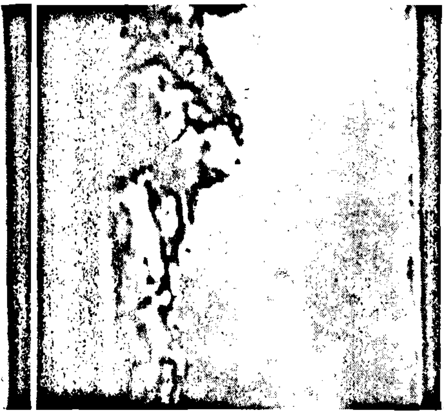


13. VOID FRACTION (α)

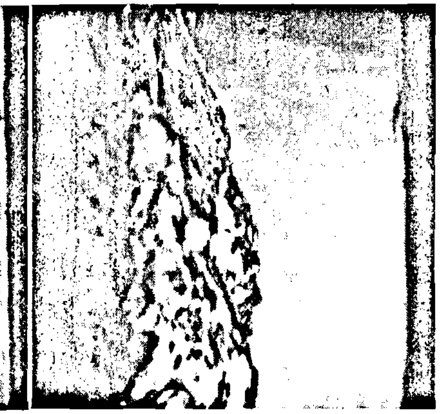
Vapor film thickness



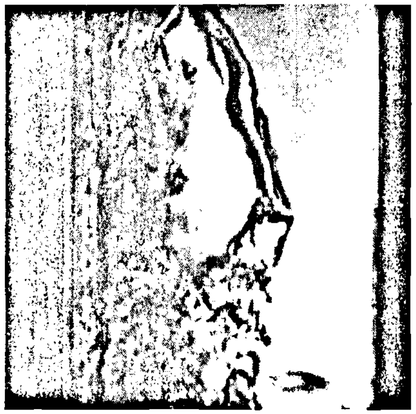
$z = 2.5\ cm$



$z = 7.6\ cm$

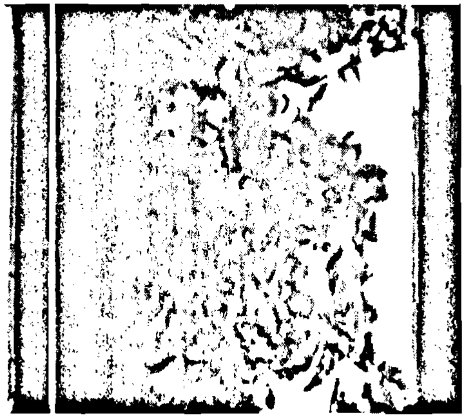


$z = 12.7\ cm$



$z = 17.8\ cm$

$z = 22.8\ cm$

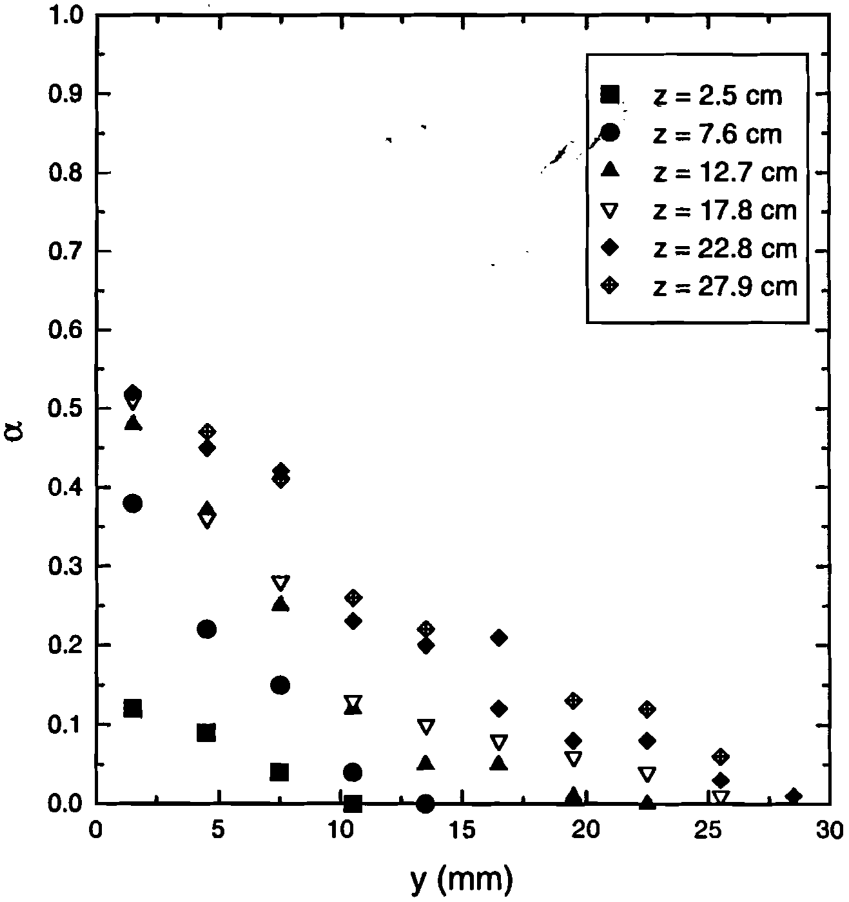


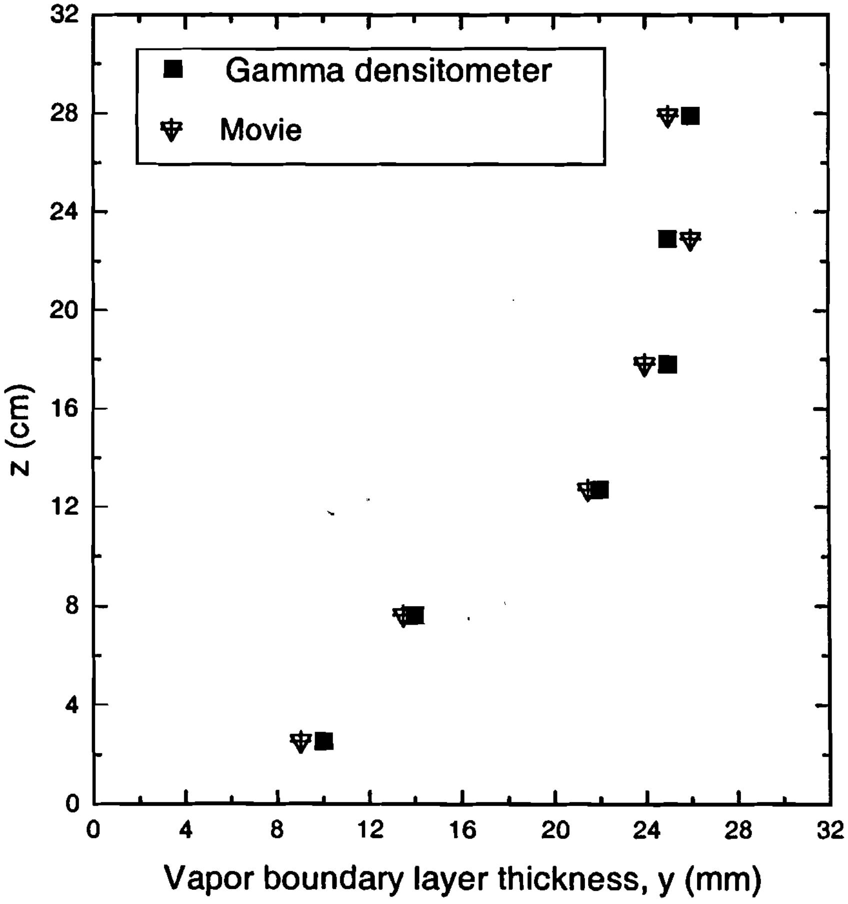
$z = 27.9\ cm$

Sequence: Left to right and top to bottom

13. VOID FRACTION (contd.)

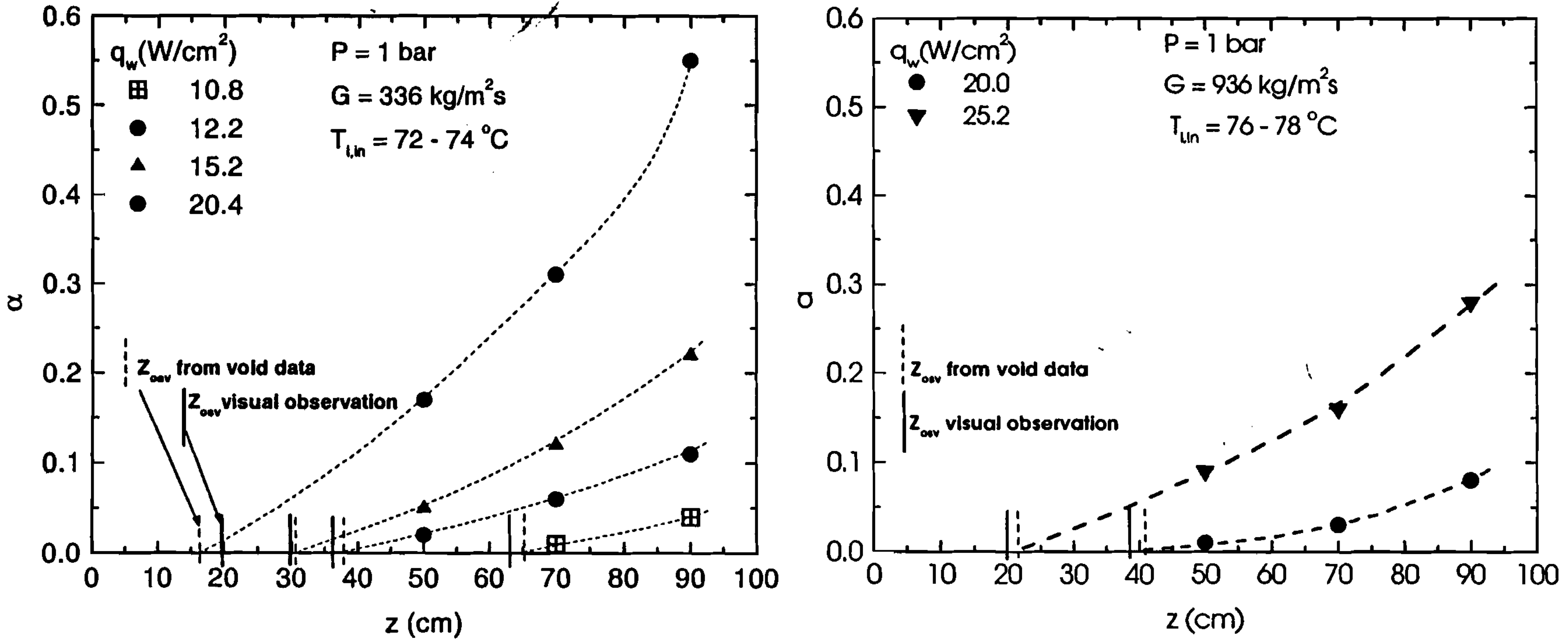
Flat Plate data



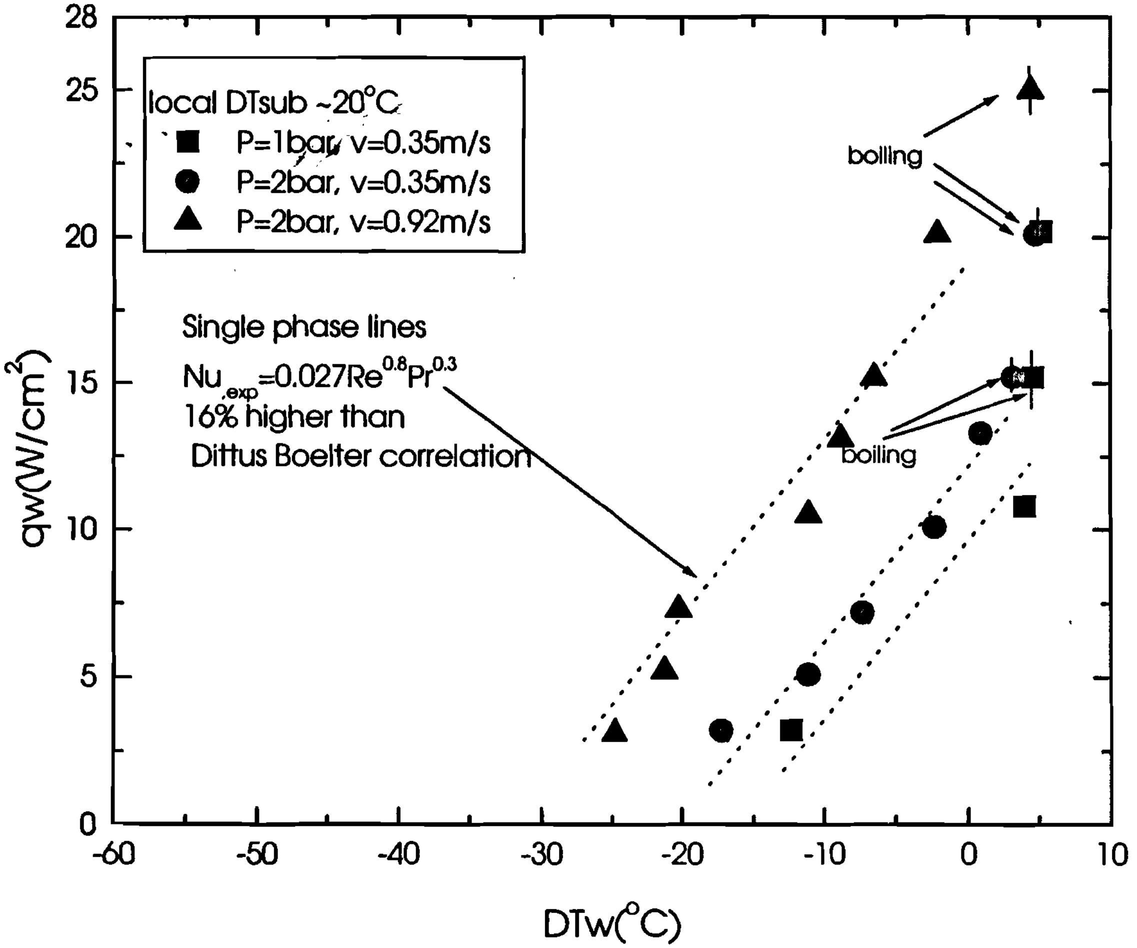


13. VOID FRACTION (contd.)

Rod -Bundle data for two different flow rates

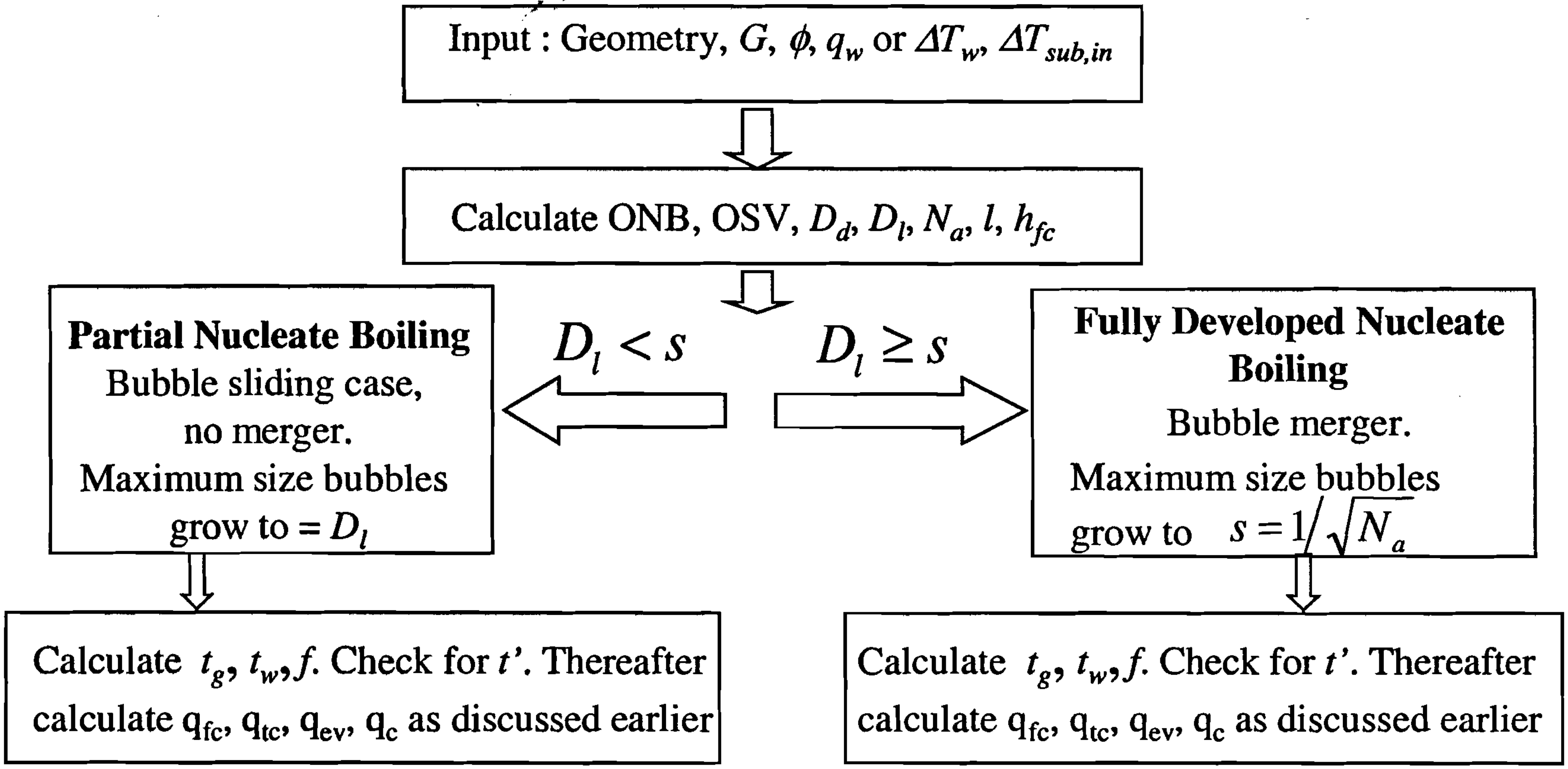


BOILING CURVE FOR DIFFERENT PRESSURES AND VELOCITIES



TASK 7
DEVELOPMENT OF VALIDATED SUBCOOLED FLOW BOILING MODEL

Procedure for Calculation



Input : Geometry, G, ϕ, q_w or ΔT_w, $\Delta T_{sub,in}$

Calculate ONB, OSV, D_d, D_l, N_a, l, h_{fc}

$D_l < s$

Partial Nucleate Boiling
Bubble sliding case,
no merger.
Maximum size bubbles
grow to = D_l

Calculate t_g, t_w, f. Check for t'. Thereafter calculate q_{fc}, q_{tc}, q_{ev}, q_c as discussed earlier

$D_l \geq s$

Fully Developed Nucleate Boiling
Bubble merger.
Maximum size bubbles
grow to $s = 1/\sqrt{N_a}$

Calculate t_g, t_w, f. Check for t'. Thereafter calculate q_{fc}, q_{tc}, q_{ev}, q_c as discussed earlier

TASK 7 (contd.)

Partial nucleate boiling wall heat flux components

1. Transient conduction component

$$\frac{Q_{tc}}{A_h} = \frac{1}{t_w + t_g}\int_0^t \frac{k}{\sqrt{\pi \alpha_l t}} \left(\Delta T_w + \Delta T_{sub}\right)\underbrace{(CD_l l)}_{A_{sl}} N_a \, dt$$

(i) $t = t'$ when $t' < (t_w + t_g)$

Forced convection for time t' to $(t_g + t_w)$ over sliding area

(ii) $t = t_g + t_w$ when $t' \geq (t_w + t_g)$

•Active nucleation site density (N_a)	From the correlation developed in the present study. It is a function of only ΔT_w and ϕ .
•Bubble lift-off diameter (D_l)	D_l from preliminary correlation obtained as function of v, ΔT_{sub}, and ΔT_w
•Bubble release frequency ($f = 1/(t_g + t_w)$)	From experimental data for flat plate as a function of D_d, ΔT_{sub}, and ΔT_w.
•Sliding distance (l)	Depends on velocity. Presently assumed to be half spacing length
•Bubble base diameter coefficient (C)	Assumed to be 0.85
•Time for transient conduction(t')	From forced convection and transient conduction heat transfer coefficients

TASK 7 (contd.)

Partial nucleate boiling wall heat flux components (contd.)

2. Forced convection component

$$\frac{Q_{fc}}{A_h} = \overline{h_{fc}}(\Delta T_w + \Delta T_{sub})[1 - A_{sl} N_a] + \overline{h_{fc}}(\Delta T_w + \Delta T_{sub}) A_{sl} N_a (1 - \frac{t'}{t_w + t_g})$$

•Single phase heat transfer coefficient (h_{fc})	Enhanced heat transfer coefficient due to the presence of bubbles, obtained from the experimental values
•Active nucleation site density (N_a)	From the correlation developed in the present study as a function of only ΔT_w and ϕ .
•Bubble lift-off diameter (D_l)	D_l from preliminary correlation obtained as function of v, ΔT_{sub}, and ΔT_w
•Bubble base diameter coefficient (C)	Assumed to be 0.85
•Bubble release frequency ($f=1/(t_g + t_w)$)	From experimental data for flat plate as a function of D_d, ΔT_{sub}, and ΔT_w .
•Time for transient conduction(t')	From forced convection and transient conduction heat transfer coefficients

TASK 7 (contd.)

Partial nucleate boiling wall heat flux components (contd.)

3. Condensation component (stationary and sliding bubbles)

$$\frac{Q_c}{A_h} = \overline{h_c A_c} N_a \Delta T_{sub} \qquad \overline{h_c A_c} = f \int_0^{t_g} h_c(t) A_c(t)\,dt$$

•Condensation heat transfer coefficient (*hc*)	Using Ranz and Marshall correlation for convection around a sphere.
•Area of condensation (*Ac*)	Half the surface area of a bubble of size $D_l/2$
•Active nucleation site density (N_a)	From the correlation developed in the present study
•Bubble lift-off diameter (D_l)	D_l from preliminary correlation obtained as function of v, ΔT_{sub}, *and* ΔT_w
•Bubble release frequency ($f=1/(t_g + t_w)$)	From experimental data for flat plate as a function of D_d, ΔT_{sub}, *and* ΔT_w.

TASK 7 (contd.)

Partial nucleate boiling wall heat flux components

4. Evaporative component $$\frac{Q_{ev}}{A_h} = \rho_v h_{fg} \frac{\pi}{6} D_l^3 N_a f$$

•Active nucleation site density (N_a)	From the correlation developed in the present study. Is a function of only ΔT_w and ϕ .
•Bubble lift-off diameter (D_l)	D_l from preliminary correlation obtained as function of v, ΔT_{sub}, *and* ΔT_w
•Bubble release frequency *($f=1/(t_g + t_w)$)*	From experimental data for flat plate as a function of D_d, ΔT_{sub}, *and* ΔT_w .

TASK 7 (contd.)

Fully developed nucleate boiling wall heat flux components (contd.)

1. Transient conduction component

$t' \le t_w$

$$\frac{Q_{tc}}{A_h} = \frac{1}{t_w + t_g}\int_0^{t'} \frac{k}{\sqrt{\pi \alpha_l t}}\left(\Delta T_w + \Delta T_{sub}\right)dt$$

$t' > t_w$

$$\frac{Q_{tc}}{A_h} = \frac{1}{t_w + t_g}\left[\begin{array}{l}\displaystyle\int_0^{t_w} \frac{k}{\sqrt{\pi \alpha_l t}}\left(\Delta T_w + \Delta T_{sub}\right)dt + \\ \displaystyle\int_{t_w}^{t} \frac{k}{\sqrt{\pi \alpha_l t}}\left(\Delta T_w + \Delta T_{sub}\right)\left[1 - \left(\frac{\pi}{4}Cs\right)^2 N_a\right]dt\end{array}\right]$$

$t = t_g + t_w$ if $t' > t_g + t_w$, else $t = t'$.

•Active nucleation site density (*N_a*)	From the correlation developed in the present study as a function of only ΔT_w and ϕ .
•Maximum Bubble diameter (*s*)	*s* is equal to spacing *s*, when merging.
•Bubble release frequency (*f=1/(tw+tg)*)	From experimental data corresponding to bubble size (D_d or s as per the case), ΔT_{sub}, *and* ΔT_w .
•Bubble base diameter coefficient (*C*)	Assumed to be 0.85
•Time for transient conduction(*t'*)	From forced convection and transient conduction heat transfer coefficients

TASK 7 (contd.)

Fully developed nucleate boiling wall heat flux components (contd.)

2. Forced convection component

$$t' \le t_w \longrightarrow \frac{Q_{fc}}{A_h} = \overline{h_{fc}}(\Delta T_w + \Delta T_{sub})\frac{t_w - t'}{(t_g + t_w)} + \overline{h_{fc}}(\Delta T_w + \Delta T_{sub})\left[1 - \frac{\pi}{4}(Cs)^2 N_a\right]\frac{t_g}{(t_g + t_w)}$$

$$t_w < t' < (t_w + t_g) \rightarrow \frac{Q_{fc}}{A_h} = \overline{h_{fc}}(\Delta T_w + \Delta T_{sub})\left[1 - \frac{\pi}{4}(Cs)^2 N_a\right]\frac{t_g + t_w - t'}{(t_g + t_w)}$$

$t' \ge (t_w + t_g) \longrightarrow$ No forced convection

•Active nucleation site density (N_a)	From the correlation developed in the present study as a function of only ΔT_w and ϕ .
•Maximum Bubble diameter (s)	s is equal to spacing s, when merging.
•Bubble base diameter coefficient (C)	Assumed to be 0.85
•Bubble release frequency ($f=1/(tw+tg)$)	From experimental data corresponding to bubble size (D_d or s as per the case), ΔT_{sub}, *and* ΔT_w .
•Time for transient conduction(t')	From forced convection and transient conduction heat transfer coefficients

TASK 7 (contd.)

Fully developed nucleate boiling wall heat flux components (contd.)

3. Condensation component (attached bubbles)

$$\frac{Q_c}{A_h} = \overline{h_c A_c} N_a \Delta T_{sub} \qquad \overline{h_c A_c} = f \int_0^{t_g} h_c(t) A_c(t) dt$$

•Condensation heat transfer coefficient (*hc*)	Using Ranz and Marshall correlation for convection around a sphere.
•Area of condensation (*Ac*)	Half the surface area of a bubble corresponding to bubble of size *s/2*
•Active nucleation site density (N_a)	From the correlation developed in the present study as a function of only ΔT_w and ϕ .
•Bubble release frequency (*f=1/(tw+tg)*)	From experimental data corresponding to bubble size (D_d or *s* as per the case), ΔT_{sub}, *and* ΔT_w .

TASK 7 (contd.)

Fully developed nucleate boiling wall heat flux components (contd.)

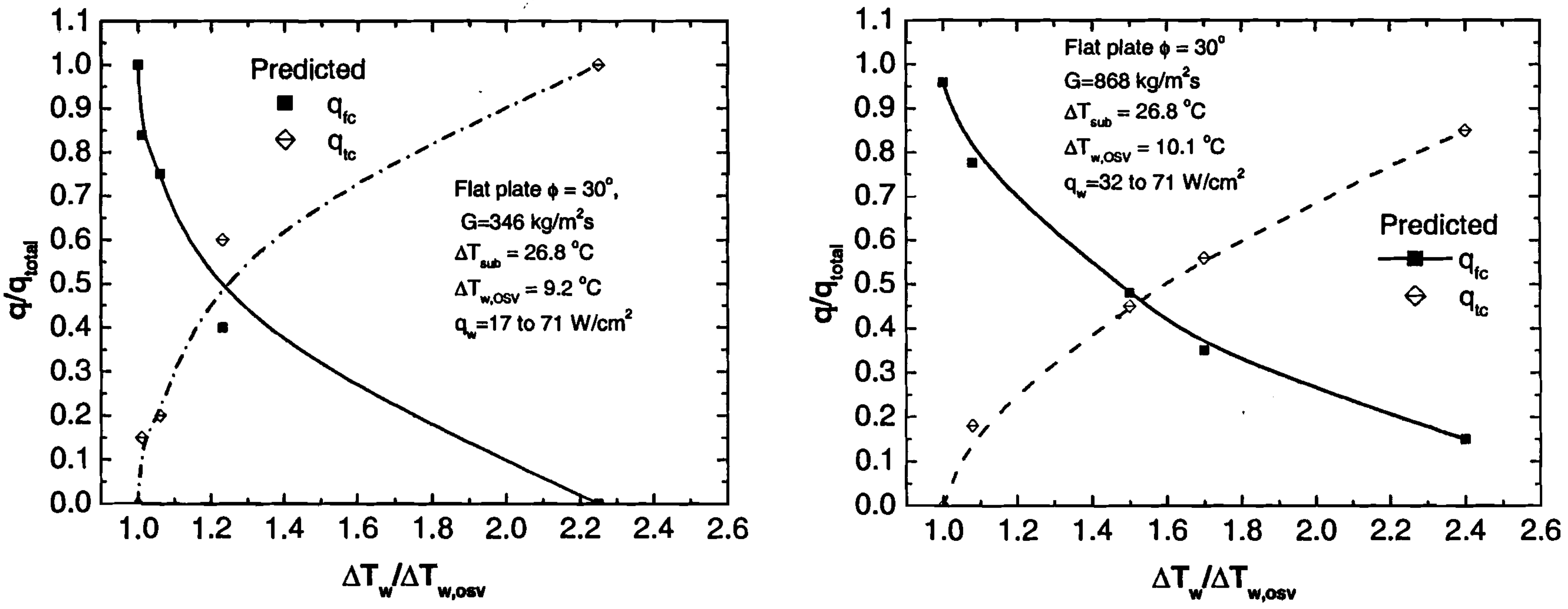
4. Evaporative component

$$\frac{Q_{ev}}{A_h} = \rho_v h_{fg} \frac{\pi}{6} s^3 N_a f$$

•Active nucleation site density (N_a)	From the correlation developed in the present study as a function of only ΔT_w and ϕ .
•Bubble diameter (s)	s is equal to spacing s, when merging.
•Bubble release frequency ($f=1/(tw+tg)$)	From experimental data corresponding to bubble size (D_d or s as per the case), ΔT_{sub}, and ΔT_w .

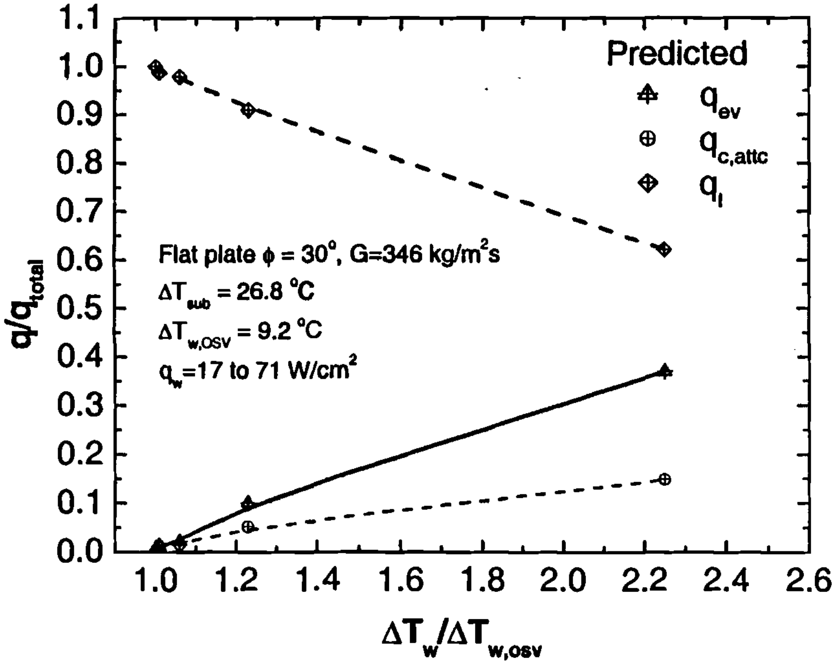
TASK 7 (contd.)

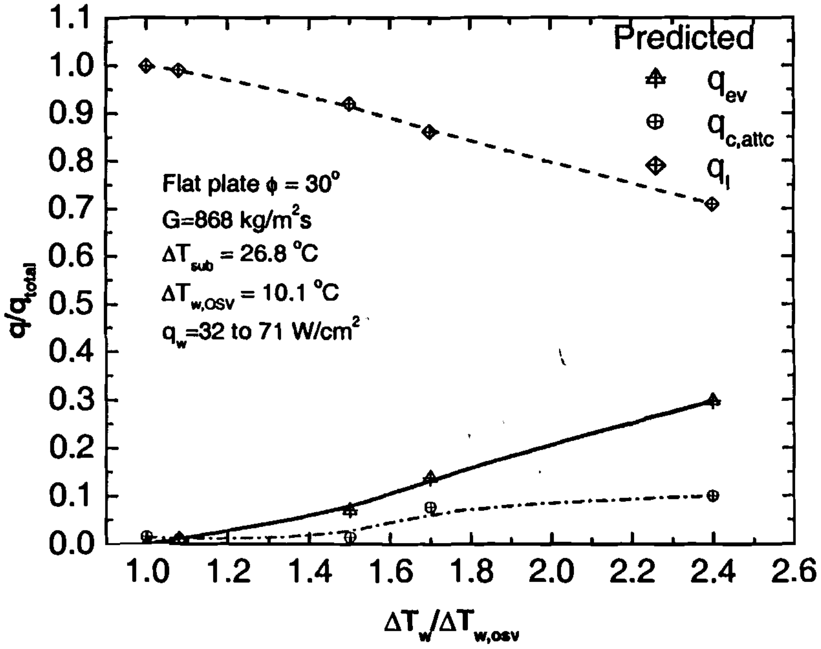
Predicted fractions of Wall Heat Flux Components-Transient Conduction and Forced Convection For Flat Plate at Two Different Flow Rates



TASK 7 (contd.)

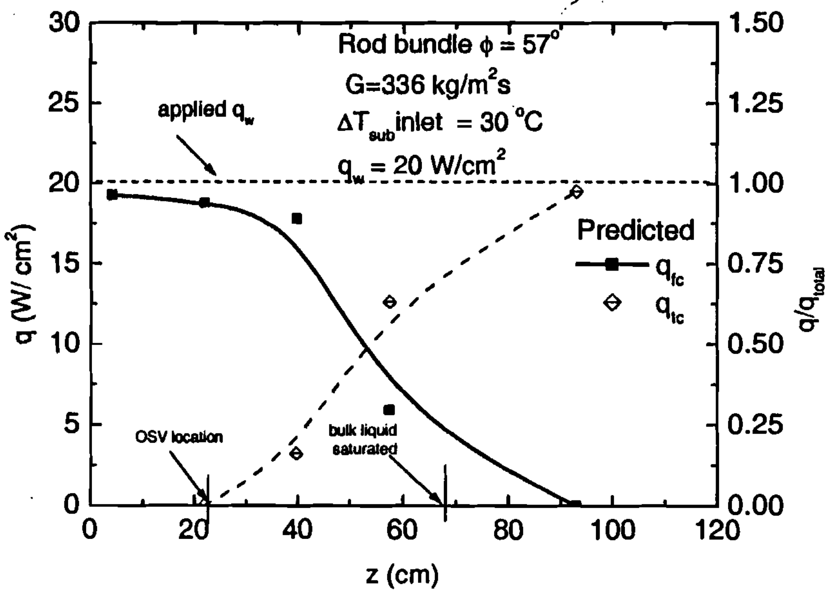
Predicted fractions of Wall Heat Flux Components-Evaporative, Condensation and Sensible Heating of Liquid For Flat Plate at Two Different Flow Rates

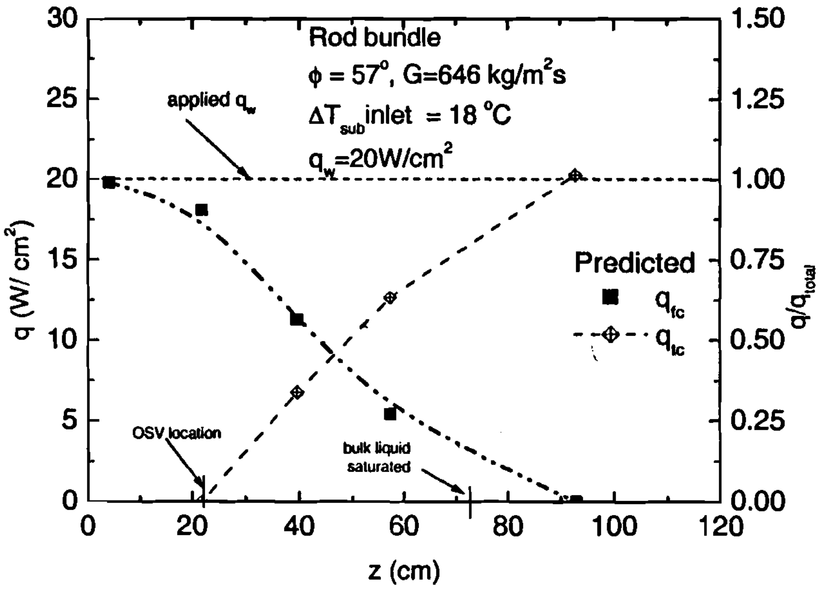




TASK 7 (contd.)

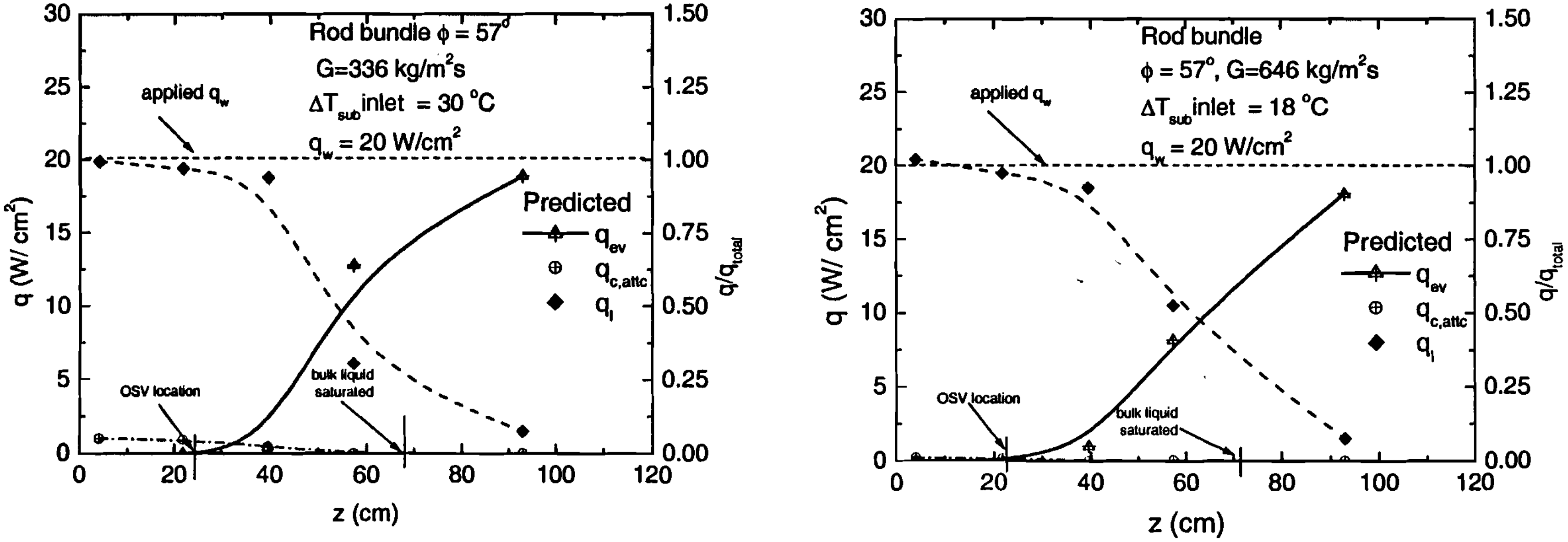
Predicted fractions of Wall Heat Flux Components- Transient Conduction and Forced Convection For Rod Bundle at Two Different Flow Rates





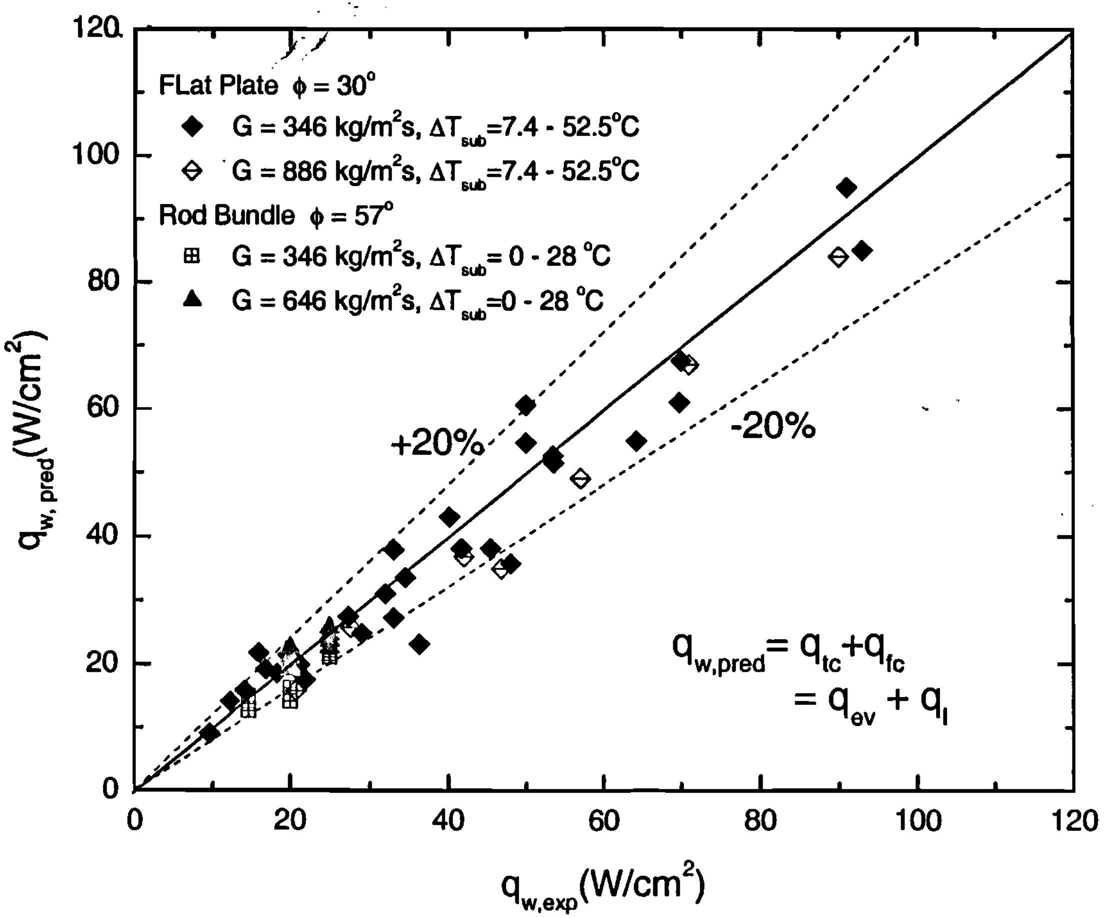
TASK 7 (contd.)

Predicted fractions of Wall Heat Flux Components- Evaporative, Condensation and Sensible Heating of Liquid For Rod Bundle at Two Different Flow Rates



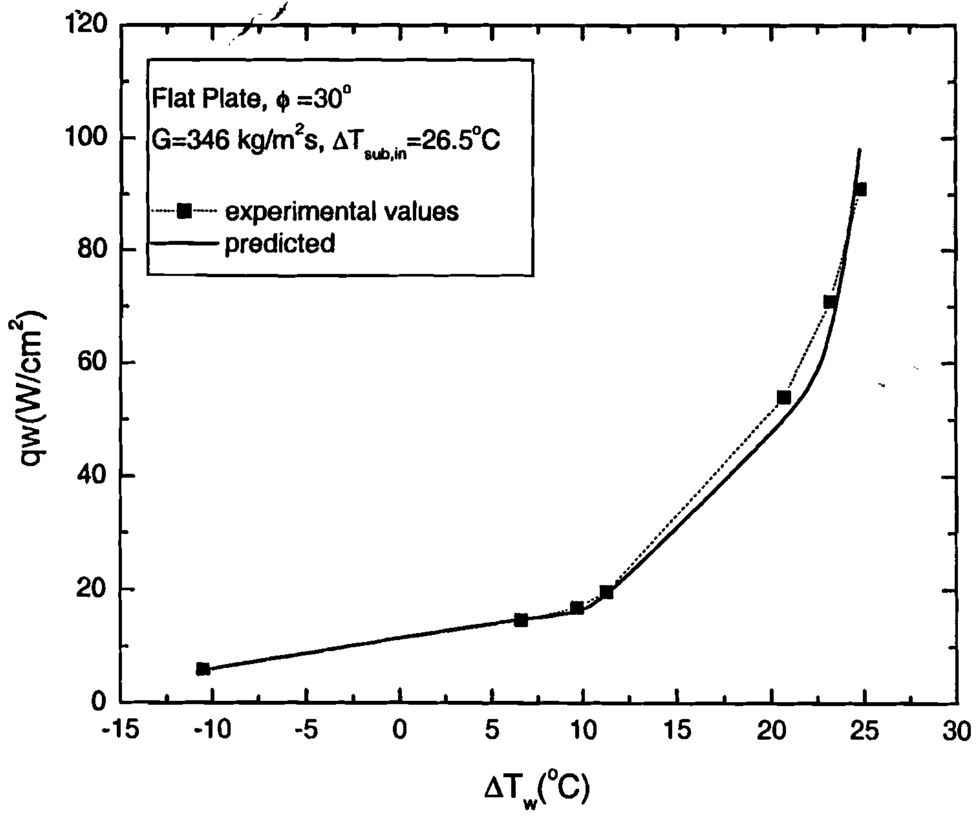
TASK 7 (contd.)

COMPARISON OF PREDICTED WALL HEAT FLUX WITH EXPERIMENTAL VALUES



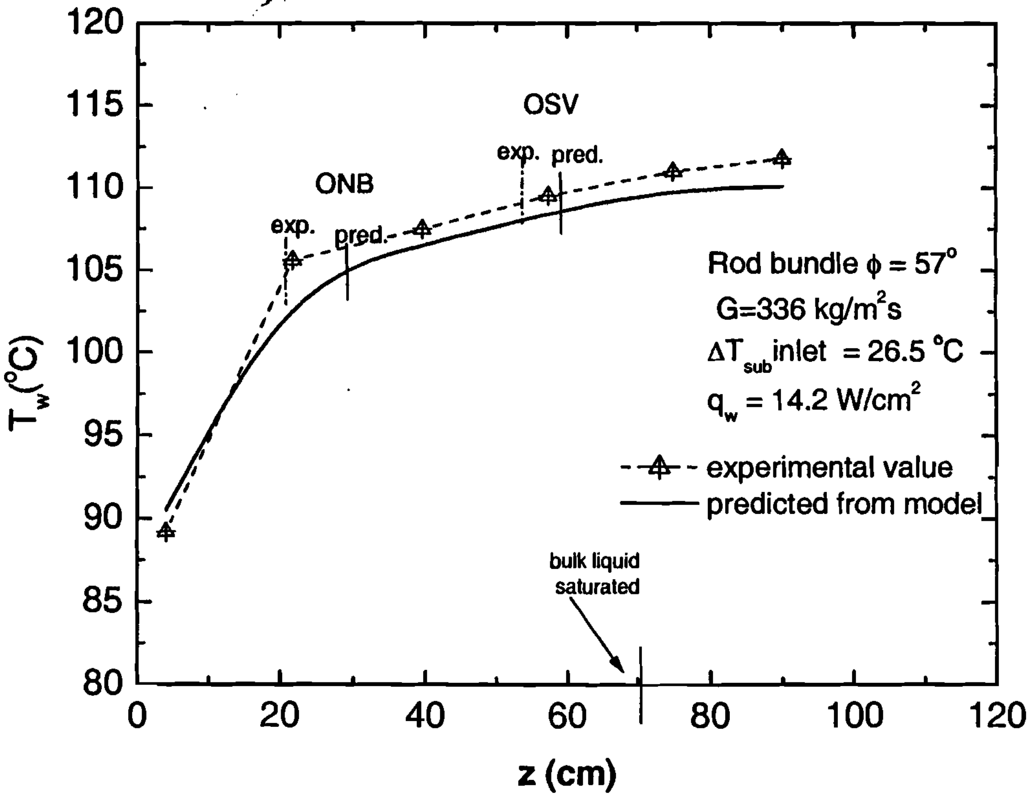
TASK 7 (contd.)

COMPARISON OF (BOILING CURVE) EXPERIMENTAL VALUES FOR FLAT PLATE WITH MODEL



TASK 7 (contd.)

COMPARISON OF PREDICTED WALL SUPERHEAT WITH EXPERIMENTAL VALUES FOR ROD BUNDLE

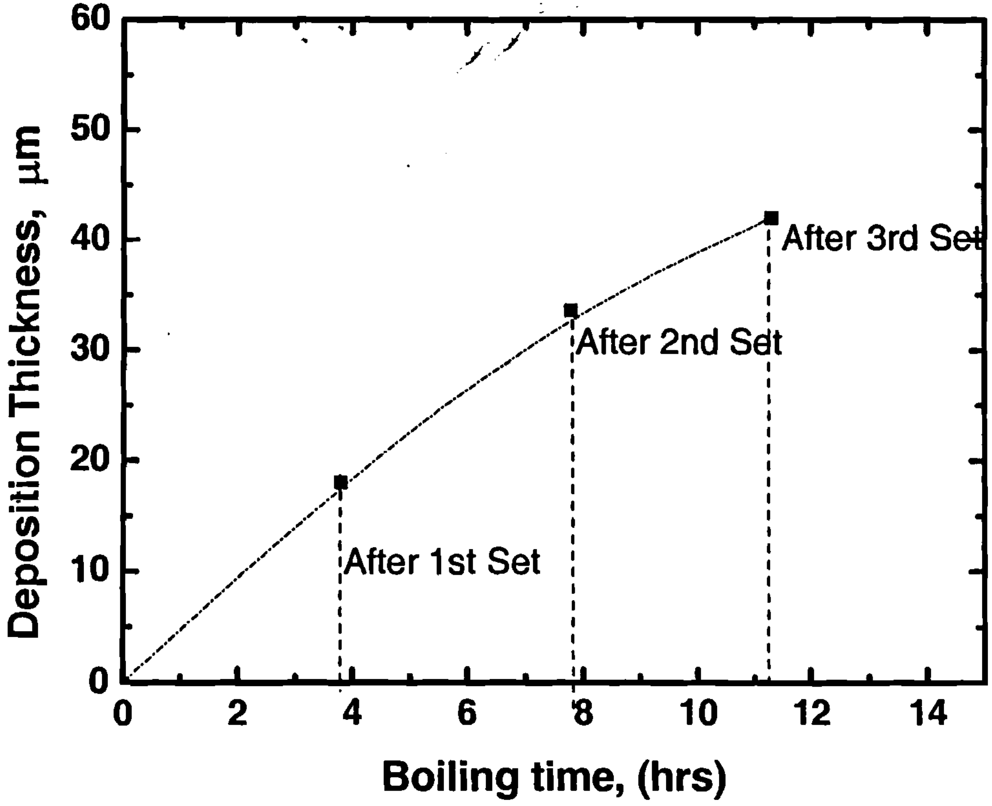


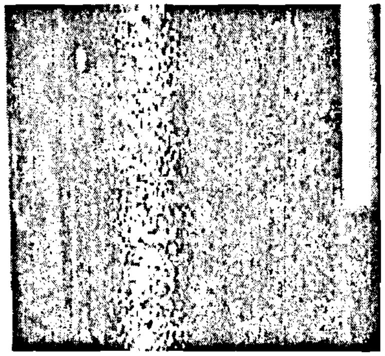
ROD BUNDLE EXPERIMENTS WITH BORON

- Three sets of subcooled flow boiling experiments were performed covering the following range of parameters:
  - P: 1.03 *bar*
  - G: 635 kg/m^2s
  - $\Delta T_{sub,in}$: 23.2 to 27.3 °C
  - q_w: 1.9, 2.9, 4.9, 6.7, 8.5, 9.7, 14.7, 19.7, 24.1, 29.2 W/cm^2
  - ϕ: 57°
  - Boron concentration: ~ 7000 ppm
- Measured parameters: (1) heat flux, (2) wall temperature, (3) liquid temperature, (4) crud thickness, (5) ONB, (6) N_a, and (7) OSV

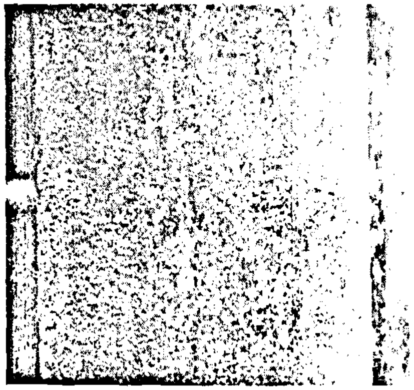
ROD BUNDLE EXPERIMENTS WITH BORON

Boron Deposition with Boiling





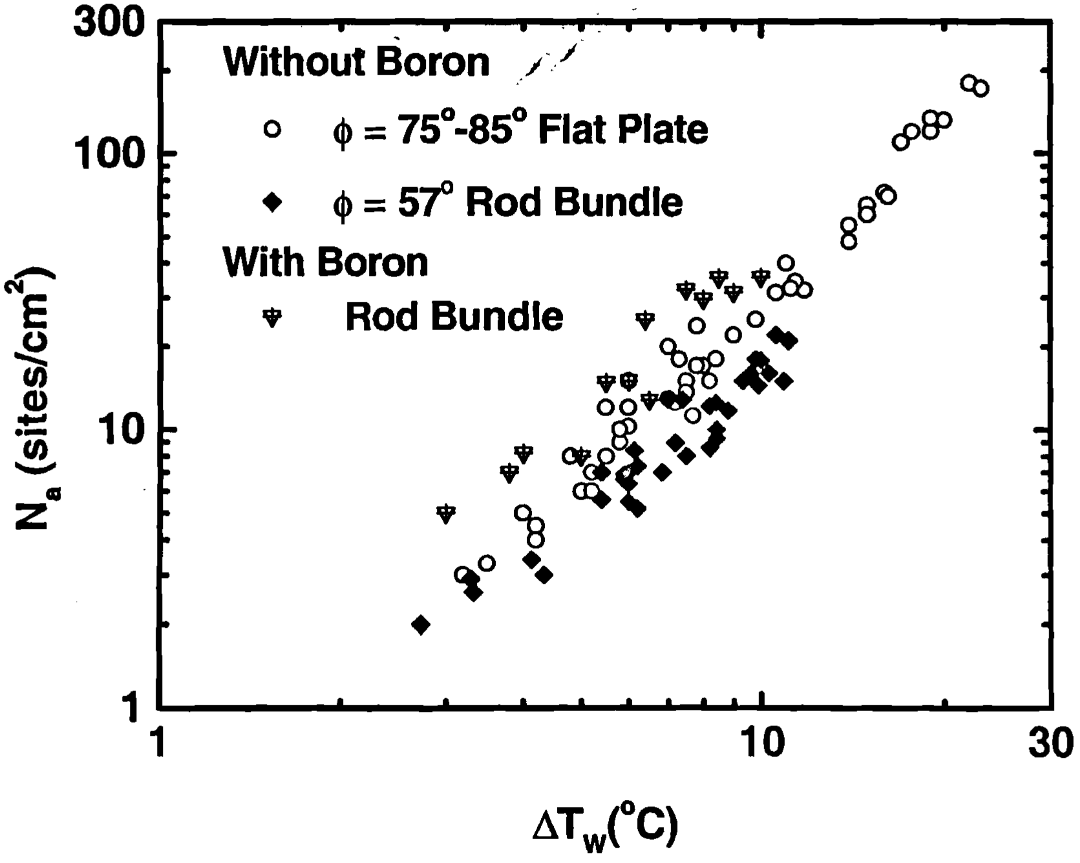
Clean Rod Surface

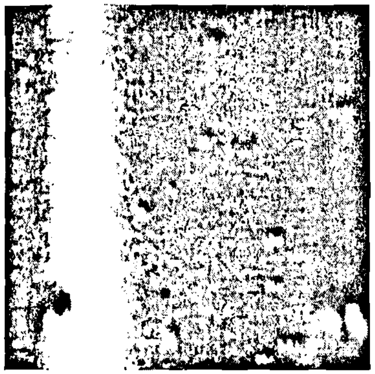


Rod Surface with Deposition

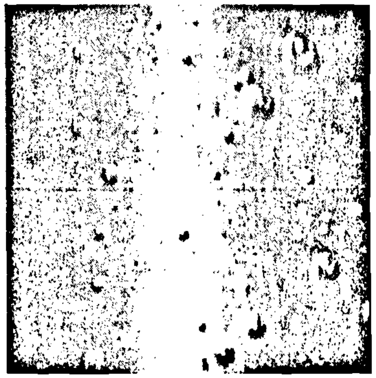
ROD BUNDLE EXPERIMENTS WITH BORON

Nucleation Site Density





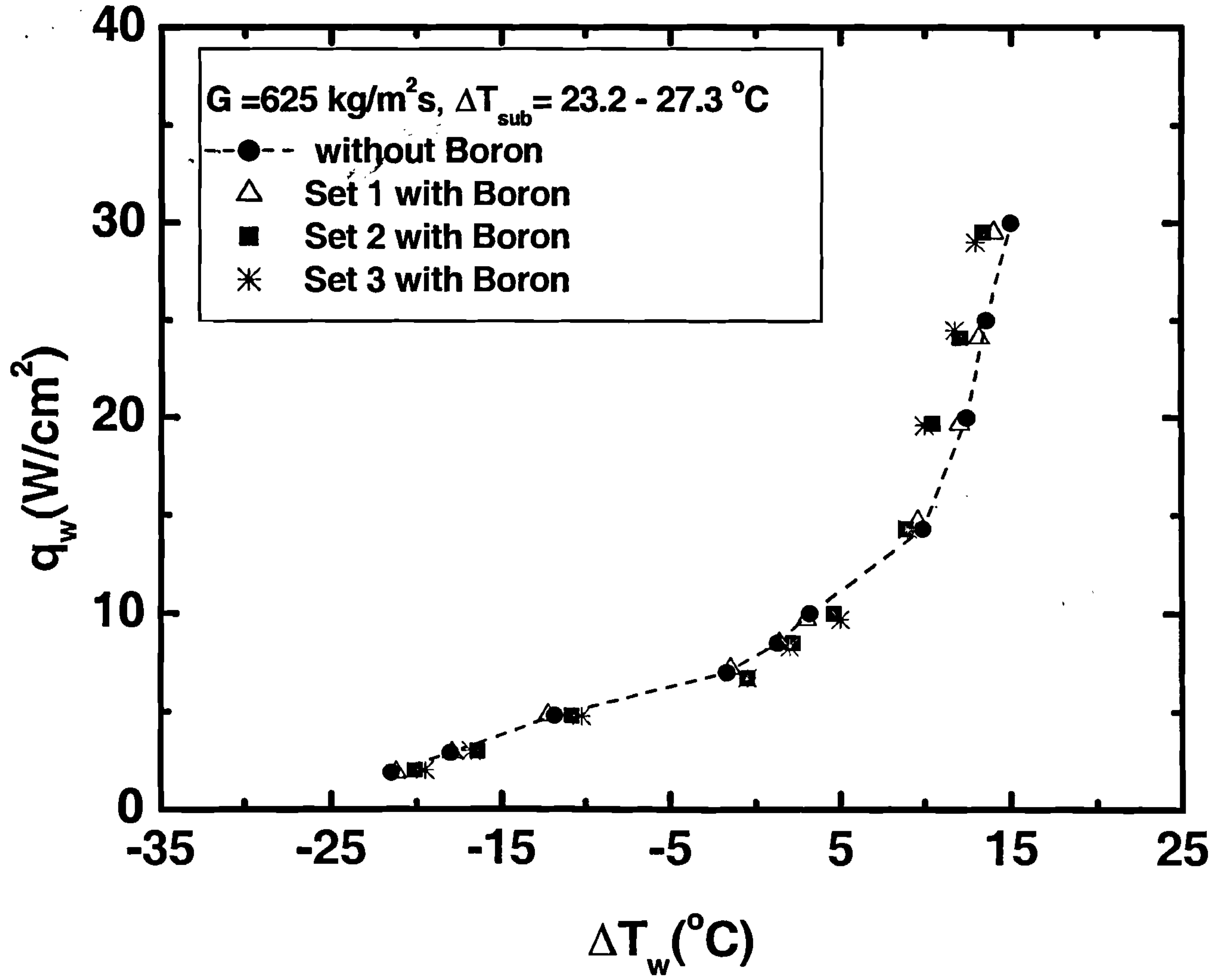
Nucleation sites on clean surface



Nucleation sites on surface with boron deposit

ROD BUNDLE EXPERIMENTS WITH BORON

Boiling Curve



FUTURE WORK

- Void fraction data for flow boiling experiments with rod bundle geometry for the following range of parameters:
  - P: 1 to 3 *bar*, G: 100 to 1000 kg/m^2s, $\Delta T_{sub,in}$: 0 to 50 °C

- Generalization of models/correlations to other pressures