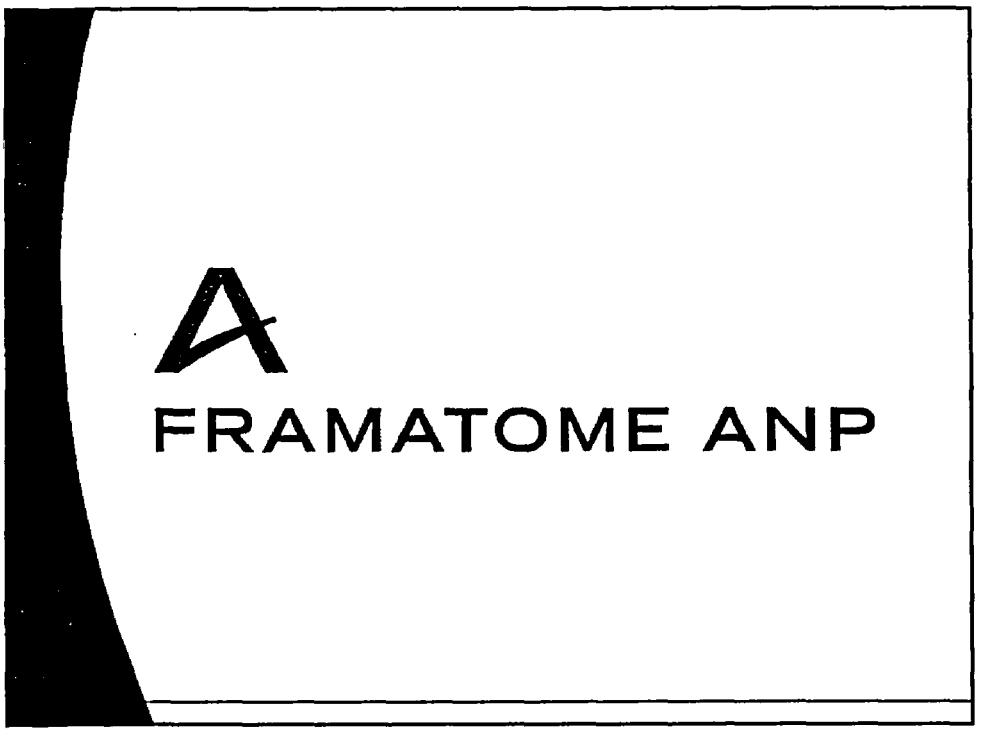

Forslund/Rohsenow Correlation

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Washington, D.C.
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Forslund/Rohsenow Correlation

- *Objective: Demonstrate that the Forslund-Rohsenow correlation is applicable to dispersed flow film boiling above Tmin*

Forslund/Rohsenow Correlation

- *Agenda*
  - *Forslund-Rohsenow Experiment**
  - *Literature Citations*

* *Dispersed Flow Film Boiling, J. Heat Transfer, 90, 6, 399 (1968)*
* *Thermal Non-Equilibrium In Dispersed Flow Film Boiling in a Vertical Tube, Massachusetts Institute of Technology, Technical Report No. 75312-44*

Purpose of Forslund's Experiment

- *"The present work extends Laverty's work by including the effects of droplet breakup, "Leidenfrost" heat transfer from the wall to the droplets, and modifies the drag coefficients for accelerating droplets."*
- *"Concern here is with the dispersed-flow-film-boiling region where heat is transferred from the wall to a possibly superheated vapor and from this vapor to liquid droplets. Superimposed on this two-step process is an additional amount of heat that transferred from the tube wall directly to the liquid droplets, a kind of Leidenfrost effect."*

Forslund's Experiment

- *Experiment Description*
  - *Experiment was designed to operate above the Leidenfrost temperature so that film boiling would exist*
  - *Test Apparatus consists of a heated tube that was injected with saturated nitrogen at 25 psia and -312°F*
    - *Tube lengths of 4 and 8 feet*
    - *Tube diameters of 0.228, 0.323, and 0.462 inches*
  - *Wall temperature data was taken at different inlet flows and power inputs*
    - *Mass Velocity from 70,000 to 190,000 lbm/hr/ft2*
    - *Heat Flux from 5,000 to 25,000 Btu/hr/ft2*

Forslund's Experiment

- *Experimental Procedure*
  - *Forslund observed that stable film boiling was consistently obtained by:*
    - *Applying heater power until the test section was above the Leidenfrost temperature*
    - *After desired temperature was reached, nitrogen flow was initiated*
    - *Full length of test section was in film boiling*
      - *CHF occurred in the nitrogen supply line to the test section*

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Forslund's Experiment

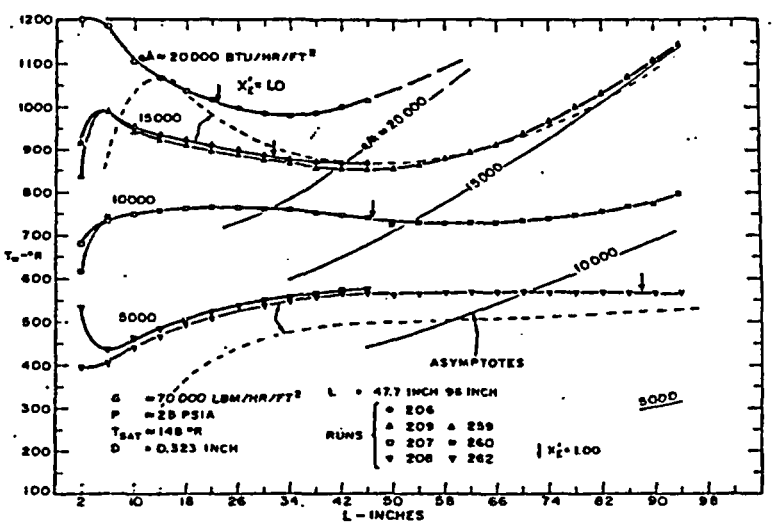

Fig. 3(a) Tube wall temperature profiles

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Forslund's Experiment

- *Hynek measured the minimum heat flux for nitrogen that would support film boiling**
  - *Conditions*
    - *Pressure = 30 psia*
    - *Heat flux = 2,200 Btu/hr/ft2*
    - *Mass Flux = 40,000 lbm/hr/ft2*
  - *Tmin = 220°R*

* *Technical Report No. 70586-63, Department of Mechanical Engineering, Massachusetts Institute of Technology*

Forslund's Experiment

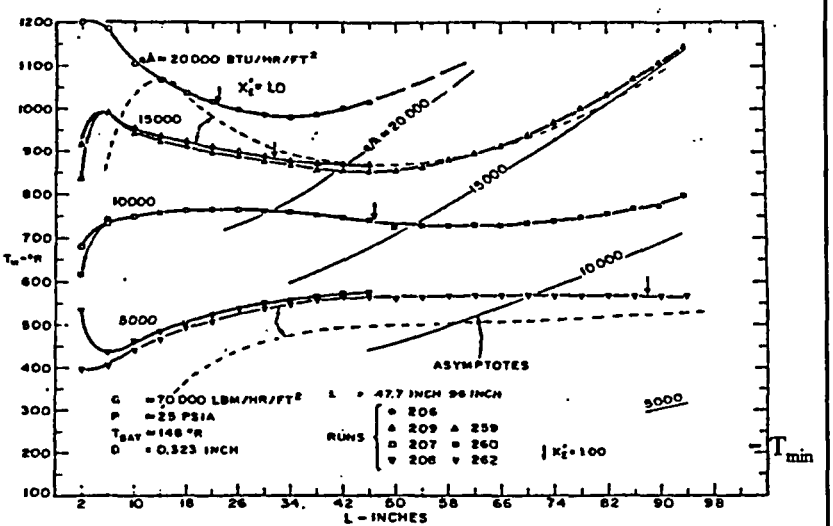

Fig. 3(a) Tube wall temperature profiles

Forslund's Experiment

- Forslund observed droplets approaching, but not touching wall
  - Dry-wall contact
- Forslund measured Q_{min} for his experimental conditions
  - Data was taken above Q_{min}, therefore, no wet wall contact
- Forslund's data exceeded T_{min}, as measured by Hynek
  - Therefore, no wet wall contact

Forslund's Experiment

- Forslund-Rohsenow Correlation
  - Based on work of Baumeister for impact of drops on a horizontally heated plate
    - Same basis as Bromley correlation
    - K. J. Baumeister, et. el., "A Generalized Correlation of Vaporization Times of Drops in Film Boiling on a Flat Plate", US-AIChE No. 120, 3rd International Heat Transfer Conference (1966)
  - Forslund's experiment was conducted in vertically heated tubes
    - Correlation was adjusted to account for this difference
      - K was 1.1 in Baumeister work
      - Final K in Forslund-Rohsenow correlation was 0.2

Literature Citations

- *Kirchner Report**
  - *Quotes*
    - *"The wall to drop convection heat transfer component is expected to be small for the temperature ranges encountered in reflooding; however, for temperatures below the minimum film boiling point, Forslund's wall-drop heat transfer term is used;"*
    - *"This result (Forslund Rohsenow correlation equ 3-33) is based on Baumeister's analysis of drops on heated surfaces (note similarity to Bromley's equation)."*
    - *"Since dispersed flow film boiling at temperatures below the minimum film boiling point occurs mostly at locations downstream of the hotspot, the choice of equation (3-33) does not have a critical influence on the overall analysis."*

* *"Reflood Heat Transfer in a Light Water Reactor," NUREG-0106, Vols. I and II, NRC-2,4 (1976)*

Literature Citations

- *Kirchner Report (cont.)*
  - *Of references reviewed todate only this report uses the Forslund-Rohsenow correlation below Tmin*
  - *Report acknowledges that this is a Bromley type correlation based on the work of Baumeister and gives no justification for use of the Forslund-Rohsenow correlation below Tmin*
    - *Only justification is that the impact is unimportant*

Literature Citations

- *M. Andreani and G. Yadigaroglu Report**
  - *Quotes*
    - *"Dispersed Flow film Boiling is the heat transfer regime that occurs at high void fractions in a heated channel."*
    - *"the heat transfer rate to the liquid phase in film boiling is calculated by using a Bromley-type correlation, that accounts for heat transfer to the bulk liquid by conduction through the vapor-film. .... It is completely arbitrary for dispersed flow, when only a small portion of the entrained liquid phase interacts with the wall." (TRAC and RELAP5)*
      - *As indicated the FORSLUND-ROHSENOW correlation is a Bromley-type correlation and has been adjusted to address the condition of droplet heat transfer in vertically heated tubes*

* *"Dispersed Flow Film Boiling," NUREG/IA-0042, 1992*

Literature Citations

- *M. Andreani and G. Yadigaroglu Report (cont)*
  - *Quotes*
    - *"The Forslund-Rohsenow correlation, as pointed out by Afifi (1985), was originally developed to account for an additional heat transfer mechanism at low quality and high mass flux, and it should give the total heat flux to the liquid."*
      - *Statement made to address the addition of the Bromley and Forslund-Rohsenow calculated heat transfer coefficients in TRAC, this is not done in S-RELAP5*
      - *From Forslund-Rohsenow paper, "An additional amount of heat transferred directly to the droplets at the wall is important at low qualities and high mass velocities."*
        - *The paper simply states that this effect is most important at low qualities and high mass velocities, it does not state or imply that it is only applicable to these conditions.*

Literature Citations

- *M. Andreani and G. Yadigaroglu Report (cont)*
  - *Quotes*
    - *"The most complete models consider DFFB as a three-path heat exchange process (three-step model), the third path being direct heat transfer from the wall to the droplets. Above a certain rewetting temperature it is commonly assumed that a droplet cannot touch the wall. "*
      - *"Forslund-Rohsenow (1968) used a heat transfer coefficient to the droplets, based on the experiments of Baumeister with nitrogen sessile drops on a horizontal heated plate: the effects of droplet velocity and concentration were correlated."*
    - *"In conclusion, a model that accounts for all the important phenomenological aspects of the DFFB that have been discussed in the present report and are not considered in the codes is not available in the literature."*

Literature Citations

- *Collier and Thom:**
  - *"Two basic approaches have been taken to estimate the heat flux to droplets entering the thermal boundary layer but which do not touch the wall. ... Alternatively, Forslund and Rohsenow (1966), Hynek et al. (1966) and Course and Roberts (1974) have assumed the heat transfer coefficient to a single droplet in the spheroidal state condition on a flat heated plate and then multiplied this by the number of droplets approaching the surface per unit time per unit area."*

* *"Convective Boiling and Condensation", J. G. Collier and J. H. Thome, Third Edition Oxford Science Publications (1996)*

Literature Citations

- *Bajorek and Young Paper**
  - *Applied Forslund-Rohsenow correlation above Tmin in dispersed flow film boiling regime*
  - *Developed a Reynolds number dependency for use with correlation replacing the correlation multiplier*
    - *Based on kinetic energy required to drive droplets towards wall and into vapor film boundary layer*
    - *Significantly improved comparisons to data*
  - *Not clear that this model is included in approved W methodology*
    - *SER approval in 1996 and paper published in December 2000*

* *"Direct-Contact Heat Transfer Model for Dispersed-Flow Film Boiling" Nuclear Technology Vol. 132 (2000)*

Conclusions

- *Conditions observed in the experiment support Forslund-Rohsenow application to dispersed film boiling above Tmin*
- *A literature review indicates that most applications of the Forslund-Rohsenow correlation are above Tmin*
  - *Only the Kirchner report actually uses the correlation below Tmin, but does not justify this application other then to indicate that it is not important*