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Vapor Condensation on a Turbulent Liquid Interface*

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ABSTRACT

The rate at which vapor condenses onto a subcooled liquid is controlled by latent heat transport from the interface into the bulk of the liquid. Turbulence on the liquid side is particularly effective in maximizing this transport. This paper describes an experimental investigation which seeks the fundamental relationship between the interfacial condensation rate and the parameters which control it when the liquid side is turbulent. The scaling laws for free-surface condensation are discussed for this case, and it is argued that the condensation of cryogenic liquids such as hydrogen can in principle be simulated with suitable experiments using steam and water. Data are presented for the condensation rate in terms of the dimensionless scaling parameters which involve the fluid properties and the liquid-side turbulence velocity and length scales, and the application of the data is discussed. It is pointed out that the steam-water condensation process becomes unstable when the liquid-side turbulence intensity exceeds a threshold value. Above the threshold, very short, high-intensity bursts of condensation occur intermittently. Our scaling laws do not apply to these bursts, and it is not known whether they can occur with typical cryogenic fluids, though we present some arguments for why they should be less likely to be triggered in cryogens.

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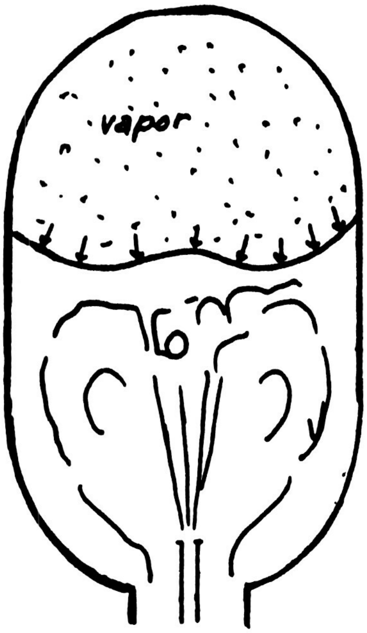
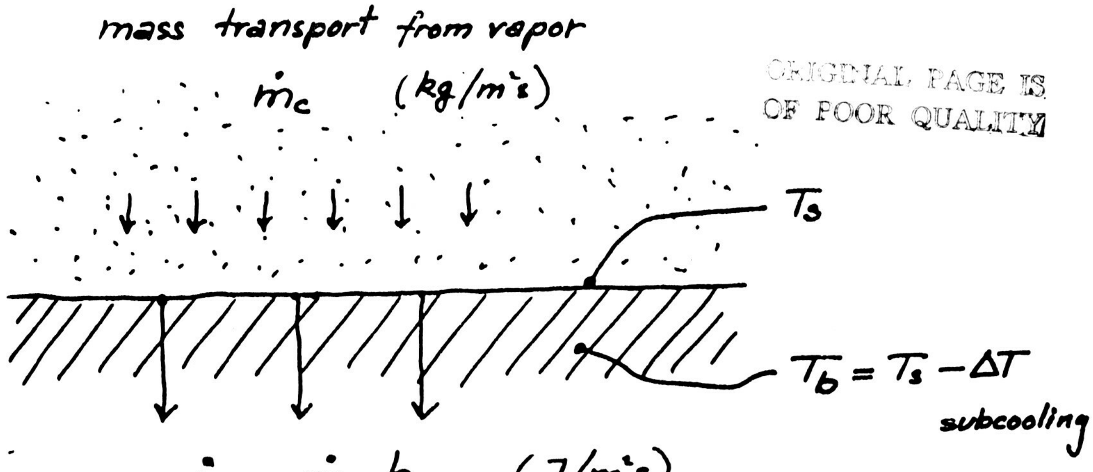


interface area
condensation rate/area
} condensation rate

max. filling rate

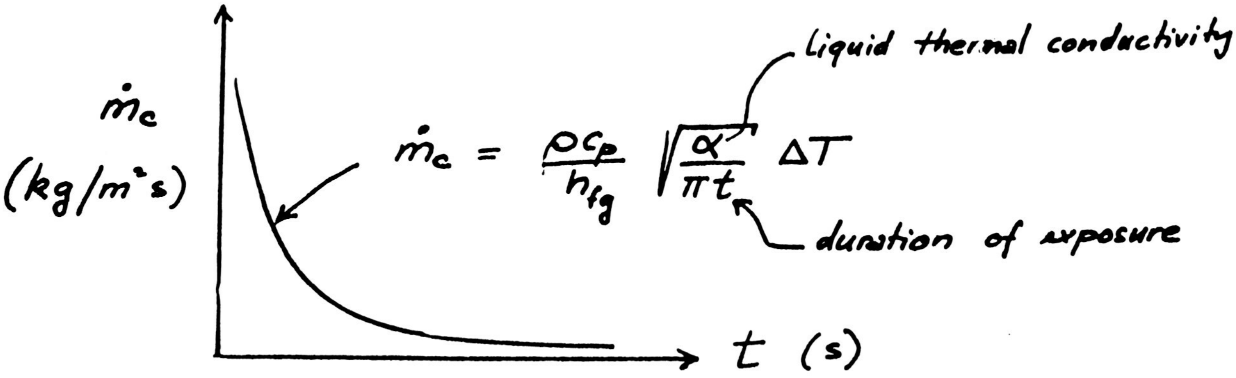
etc.



$$\dot{q}_c = \dot{m}_c h_{fg} \quad (J/m^2 s)$$

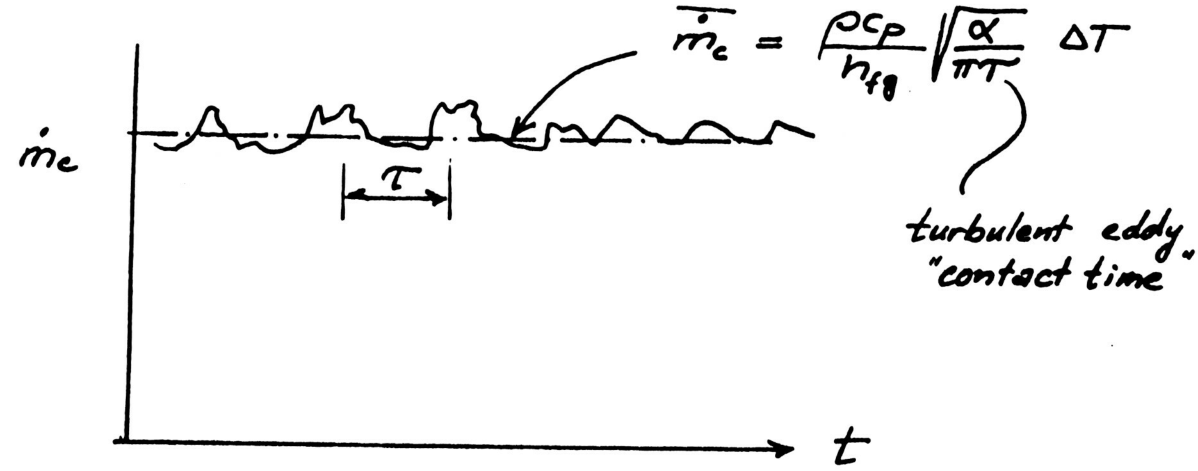
(latent) heat transport into liquid

Condensation on static liquid:



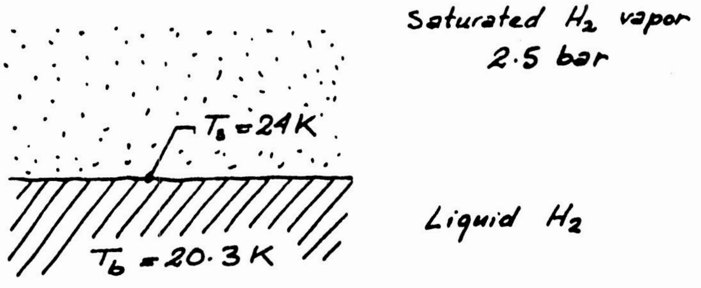
$$\dot{m}_c = \frac{\rho c_p}{h_{fg}} \sqrt{\frac{\alpha}{\pi t}} \, \Delta T$$

Condensation on turbulent liquid:



$$\overline{\dot{m}_c} = \frac{\rho c_p}{h_{fg}} \sqrt{\frac{\alpha}{\pi \tau}} \, \Delta T$$

Example



Volume of vapor condensed in 10 minutes:

(1) Static liquid — 0.02 m^3/m^2 of area

(2) Turbulent liquid, $v' = 0.1$ m/s — 1.1 m^3/m^2
(using data described later)

Characterization of condensation on turbulent liquid:

$$\boxed{St_c \equiv \frac{\dot{m}_c h_{fg}}{\rho c_p \Delta T \, v'}}$$

condensation Stanton no.

v': rms value of turbulent velocity fluctuations

Simplistic surface renewal theory:

$$St_a \sim \frac{1}{v'}\sqrt{\frac{\alpha}{\tau}}$$

α: thermal diffusivity

τ: "contact time" of turbulent eddies with surface

What determines the eddy "contact time" τ at a turbulent interface?

1. A number of simplistic models have been proposed based on
    - speculation
    - some data (e.g. gas absorption)
2. Each model "explains" some of the available data, none explains all of it.

TABLE 1: MAJOR CONCEPTUAL MODELS FOR TRANSPORT ACROSS SURFACE

MODEL	ASSUMPTIONS		CONDENSATION STANTON NO.
	diffusivity α	time scale τ	$St_c = v^{-1}(\alpha/\tau)^{1/2}$
1. Large-eddy model (Fortescue & Pearson, 1967	α	Λ/v	$St_c = c_1 Pr^{-\frac{1}{2}} Re^{-\frac{1}{2}}$
2. Small (Kolmogorov) eddy model (Lamont & Scott, 1970)	α	$(\nu\Lambda/v^3)^{1/2}$	$St_c = c_2 Pr^{-\frac{1}{2}} Re^{-\frac{1}{4}}$
3. Viscous inner layer model (see text)	α	ν/u_*^2	$St_c = c_3\ Pr^{-\frac{1}{2}}$
4. Henstock & Hanratty (1979)	α	$\nu^2/v^3\Lambda$	$St_c = c_4\ Pr^{-\frac{1}{2}} Re^{\frac{1}{2}}$
5. Levich (1962)	α	$\sigma/\rho v^3$	$St_c = c_5\ Z Pr^{-\frac{1}{2}} Re^{\frac{1}{2}}$
6. Kishinevsky (1955)	$v\Lambda$	Λ/v	$St_c = c_6$

D - liquid thermal diffusivity
v - r.m.s. turbulent fluctuating velocity
u^* - shear velocity
Λ - integral length scale of turbulent eddies
ν - liquid kinematic viscosity
ρ - liquid density
σ - surface tension

$Sc \equiv \nu/D$ Schmitt number

$Re \equiv v\Lambda/\nu$ Eddy Reynolds number

$St_c = \dfrac{\dot{m}_c h_{fg}}{\rho c_p \Delta T v}$, cond. Stanton No.

$Z \equiv (\nu^2\rho/\sigma\Lambda)^{1/2}$ Ohnesorge no.

c_1 to c_6: constants

Simulation of cryogenic fluids using steam & water

$$St_c \simeq f\left(Re\,,\ Pr_b\,,\ Pr_s\,,\ c_p\Delta T/h_{fg}\right)$$

$St_c \equiv \dfrac{\dot{m}_c\, h_{fg}}{\rho c_p \Delta T v'}$ = cond. Stanton no.

Pr_b = bulk liquid Prandtl no

Pr_s = saturation (interfacial) liquid Prandtl no.

$Re \equiv \dfrac{v'\Lambda}{\nu_b}$ = eddy Reynolds no.

Λ = turbulence macroscale

ν_b = bulk liquid kinematic viscosity

Scaling parameters for steady vapor condensation of subcooled liquid: some comparisons between hydrogen and water.

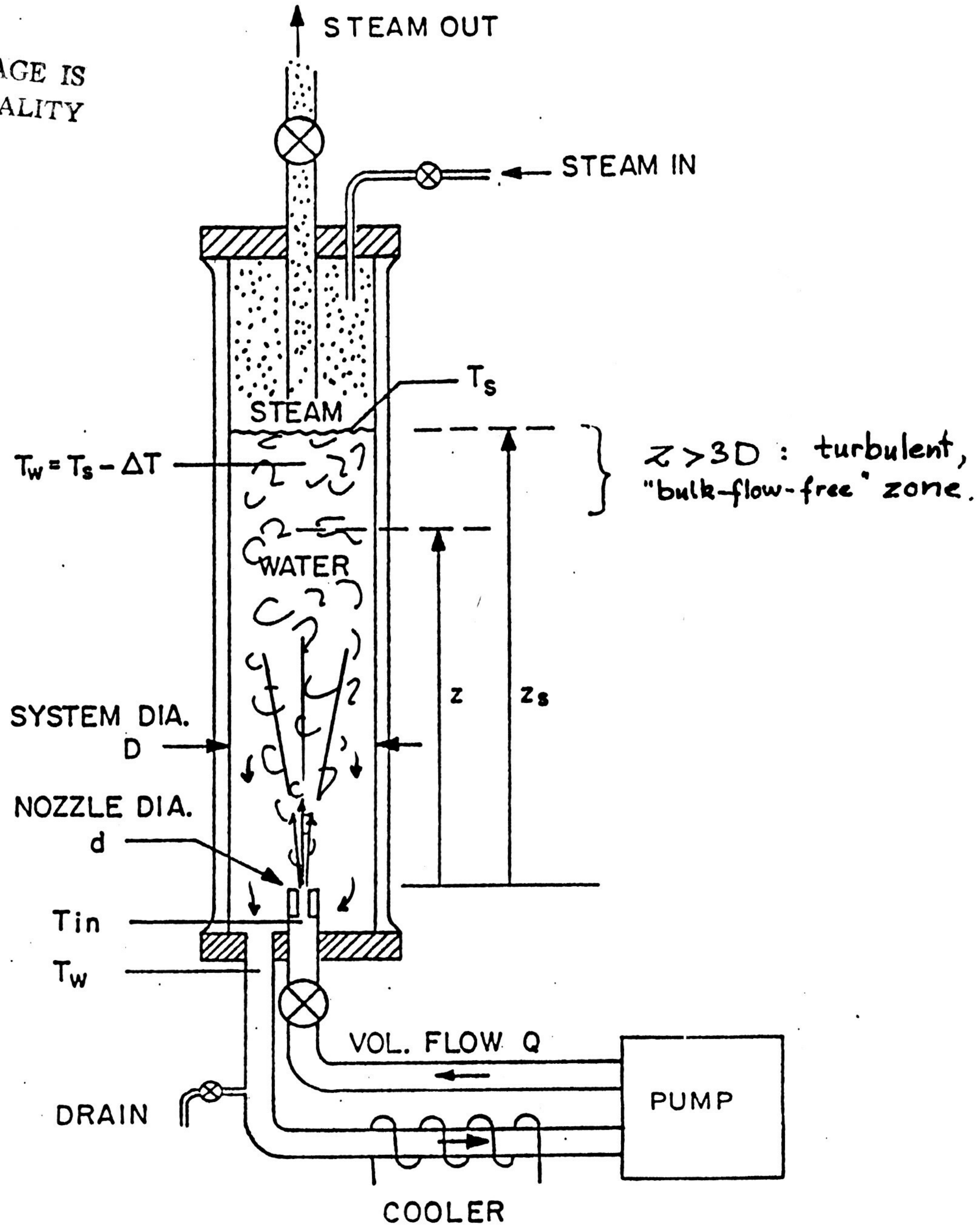
	H_2	H_2O		
Operating conditions:				
p, absolute pressure	2.5 bar (35 psia)	1.01 bar	3.19 bar	4.46 bar
T_s, saturation temperature	24K	100°C	135°C	147°C
T_b, bulk liquid temperature	20.3-24 K	20-85°C	80-135°	20-93°C
Scaling parameters:				
Pr_b, bulk liquid Prandtl number	1.3	2-7	1.3-2.2	2-7
Pr_s, liquid saturation Prandtl number	1.3	1.8	1.3	1.2
$c_p\Delta T/h_{fg}$	0-0.1	0-0.15	0-0.11	0.1-0.25

Nomenclature:

c_p - bulk liquid specific heat at constant pressure
ΔT - liquid subcooling
h_{fg} - latent heat of condensation

Subscripts:

s : at saturation temperature
b : at bulk liquid temperature


STEAM OUT
STEAM IN
Ts
STEAM
Tw = Ts − ΔT
z > 3D : turbulent, "bulk-flow-free" zone.
WATER
z
zs
SYSTEM DIA.
D
NOZZLE DIA.
d
Tin
Tw
VOL. FLOW Q
DRAIN
PUMP
COOLER

Test cell

Calibration of turbulence in test system:

Turbulence intensity (test particles, LDA):

$$v' = 21.8\,\frac{Q}{Dd}\cdot\exp\left(-1.2\,\frac{z}{D}\right)$$

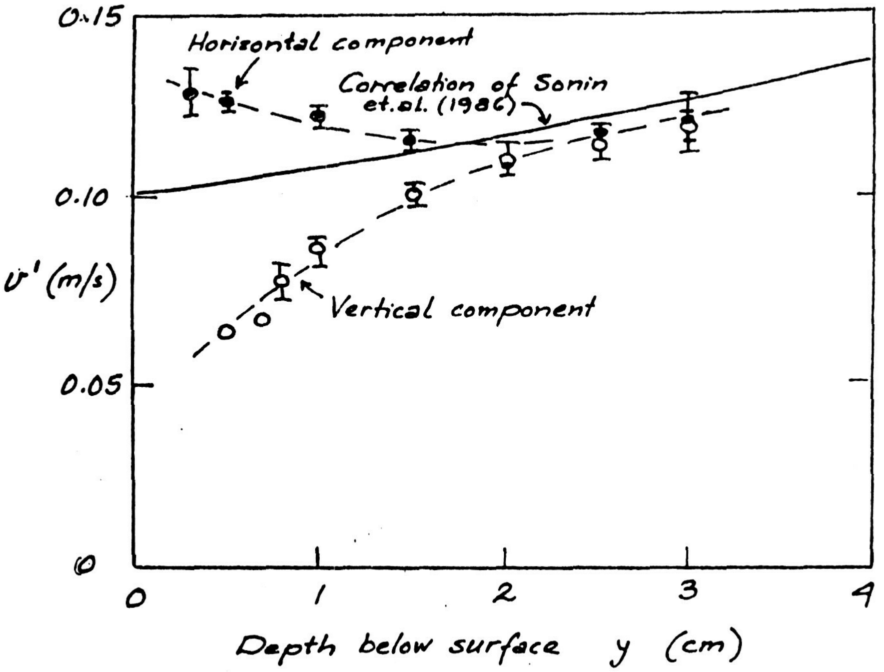
Turbulence length scale (LDA):

integral time scale from autocorrelation function.

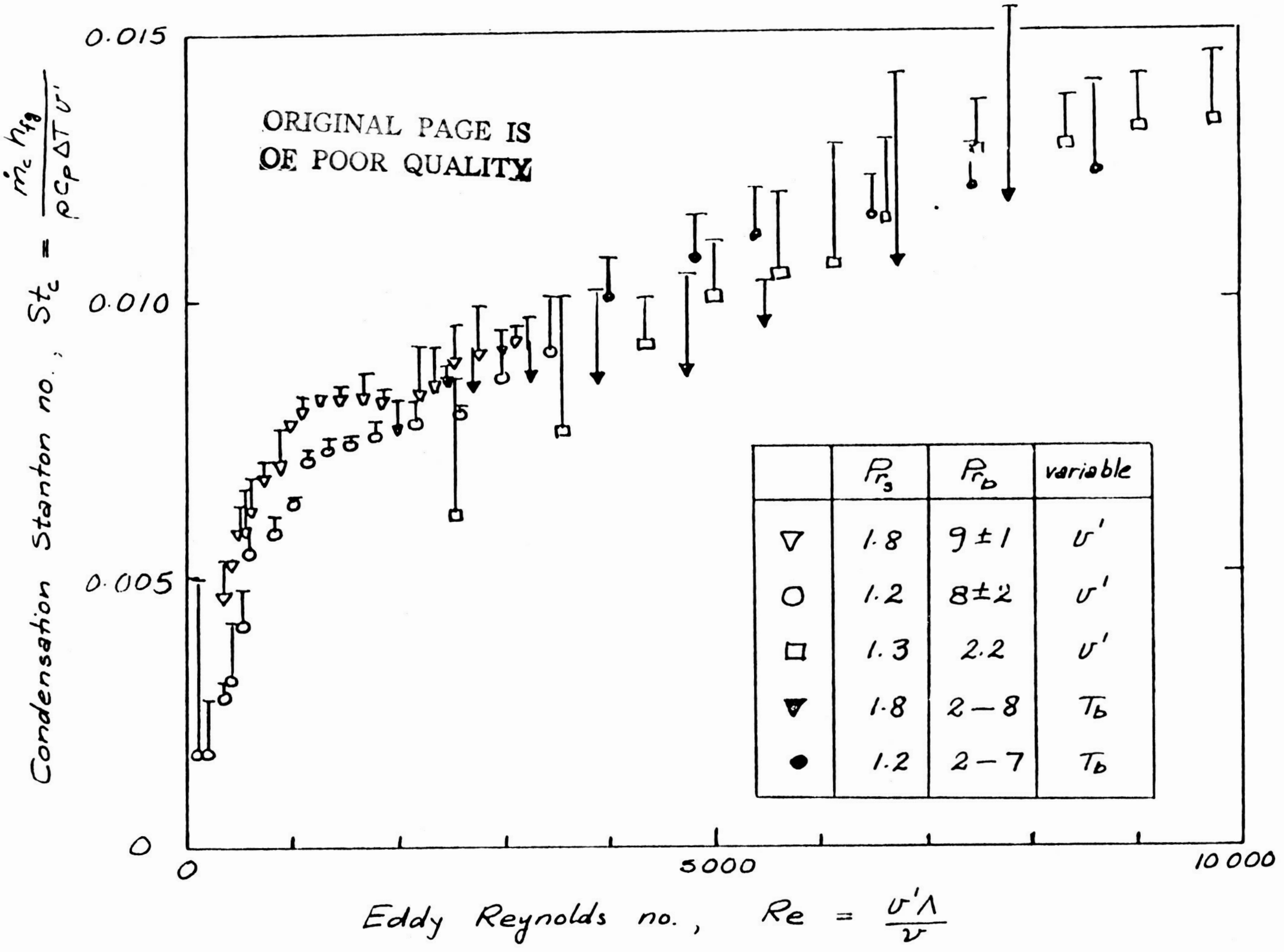
$$\Lambda \equiv v'T = 0.24\,D$$

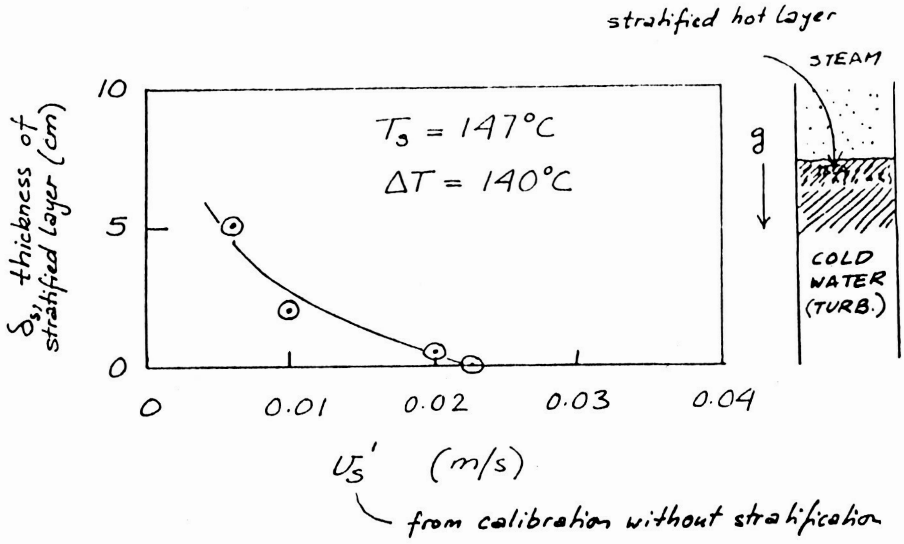
Relation of Λ to k-ε model length scale L (from matching of k-ε solution to data):

$$\Lambda = 0.22\,L$$



LDA measurements of horizontal and vertical rms velocity fluctuations in the damped layer near the interface. Also shown is the correlation of Sonin et. al. for large distances below the interface.





Visual observations of a thermal stratification at the interface at low turbulence intensities.

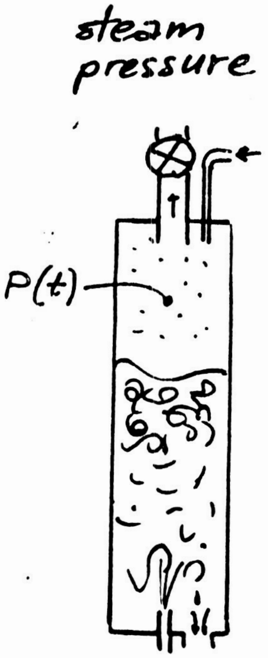
Theory based on k-ε model:

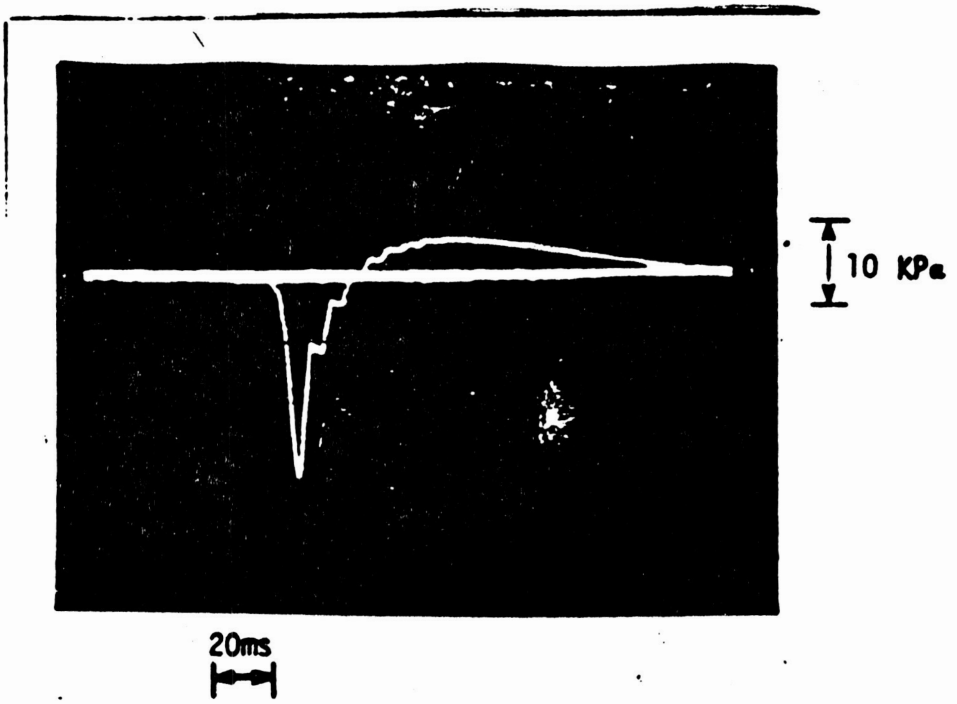
Criterion for negligible thermal stratification (damping) is

$$v_s'^2 \gg 0.0247 \ \beta \Delta T g \Lambda = (0.012 \ m/s)^2$$

Experiment (above) agrees.

Condensation bursts: an instability at high turbulence intensities.





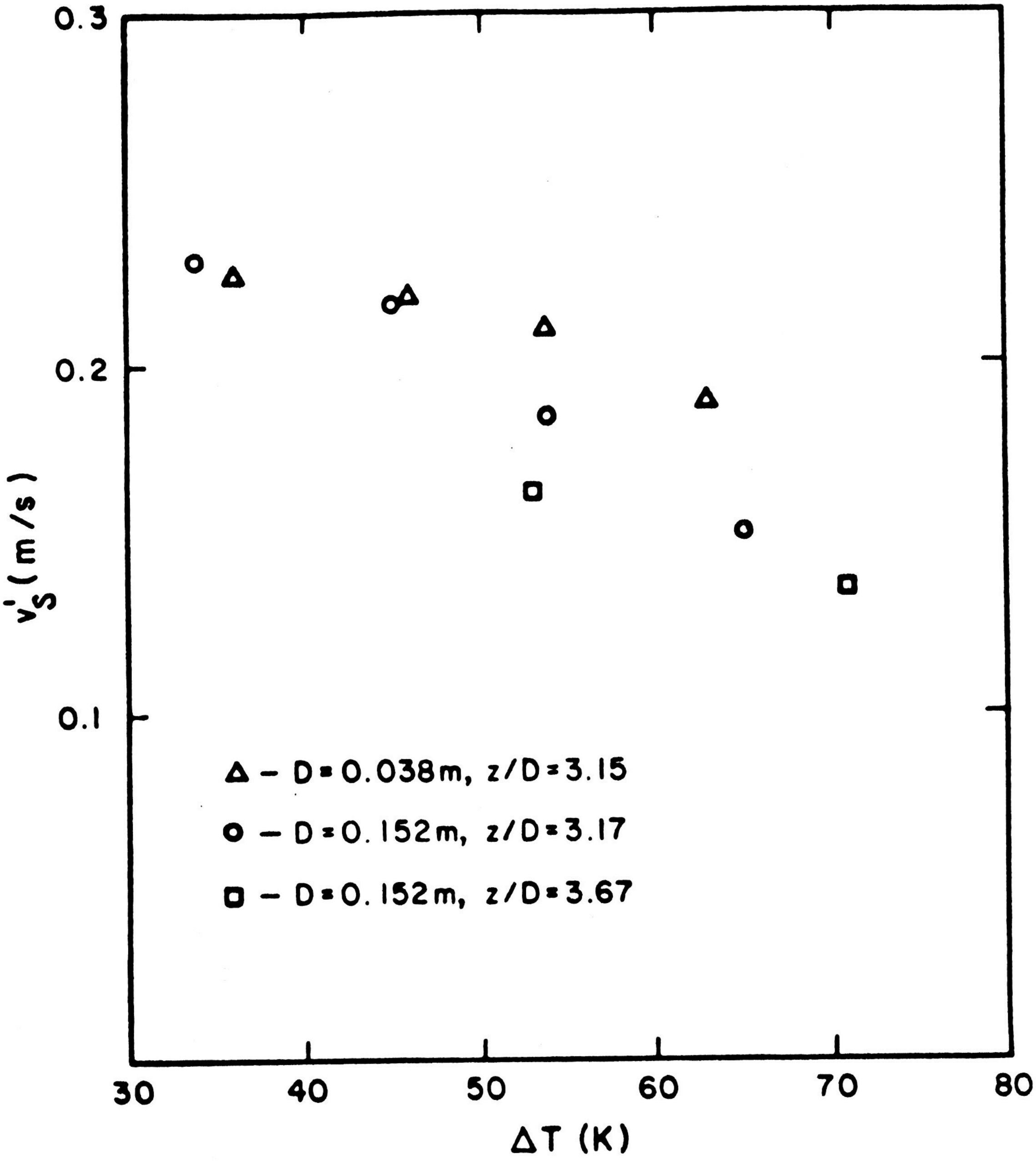
Experimental conditions

v' = 0.3 m/s

ΔT_{sub} = 60° C

H = 0.13 m

A pressure history during a condensation burst.



Threshold turbulence level for onset of condensation bursts

CONDITIONS PRIOR TO AND DURING CONDENSATION BURSTS AT $\Delta T \simeq 70^{\circ}C$.

<u>Steady state at burst threshold</u> ($v'_s = 0.15$ m/s)

condensation mass flux	$\dot{m}_c = 0.18 \text{ kg/m}^2\text{s}$
vapor momentum flux	$\dot{m}_c^2/\rho_{steam} = 0.006 \text{ mm } H_2O$
condensation heat flux into water	$q_c = 0.42 \text{ MW/m}^2$
thermal layer thickness	$\delta = 0.1$ mm

<u>Burst characteristics</u> (Anderson, 1982)

average condensation mass flux	$\dot{m}_c \simeq 20 \text{ kg/m}^2\text{s}$
average vapor momentum flux	$\dot{m}_c^2/\rho_{steam} \simeq 68 \text{ mm } H_2O$
average condensation heat flux into water	$q_c \simeq 45 \text{ MW/m}^2$
duration	$\Delta t \simeq 6$ ms
final thickness of layer heated by burst	$\delta_B \simeq 2$ mm

<u>Major Conclusions</u>

1. Condensation rate quantified in terms of

   Fluid properties
   Liquid-side turbulence characteristic v', Λ

2. Turbulence characteristics v', Λ can in principle be obtained from turbulence model (e.g. k-ϵ model)

3. High intensity condensation bursts identified at high turbulence intensities in steam/water system.

   No basic theory; not clear whether bursts will occur in cryogenic fluids.

SPEAKER: A. A. SONIN/MASSACHUSETTS INSTITUTE OF TECHNOLOGY

John R. Schuster/General Dynamics Space Systems:

It looks as though in your model that you have ignored what takes place in the vapor. Is the mass transfer process through the vapor to the liquid-vapor interface dominated by diffusion or by convection?

Sonin:

In this case, the vapor is basically considered to be still. There is no forced convection on the vapor side; there is just feeding of the vapor as it slowly moves towards the interface. Since it is just pure vapor on the vapor side it doesn't go through anything, and there is no other gas to diffuse through.

Schuster:

I understand that. It's self diffusion, yet the transport mechanism has got to be either molecular diffusion or convection.

Sonin:

It is pure convection. You have an interface and the vapor is just in bulk motion toward the interface and it disappears at the interface and turns to liquid. It moves through nothing, and not even relative to itself. There is some turbulence which is associated with it, but, basically, the controlling factor is the latent heat transport from the interface. The huge latent heat deposit at the interface has to be taken down into the bulk of the liquid, and that controls the condensation rate.

David Daney/National Bureau of Standards:

I may have observed this same type of condensation burst instability with superfluid helium during rapid pressurization of dewars and in transfer lines where a banging, crashing, and pinging noise is heard.

Sonin:

That sounds very interesting. I would like to talk with you about that afterwards. This is quite an audible instability; it is like a little crack or a snap when it occurs. What we observe when we inject steam into liquid is a sudden burst on the interface, and there is also a snap. I think it is the same thing that occurs in nuclear systems, a so called chugging, when you inject vapor into liquid and there is a sudden condensation phenomena.

Robert Hendricks/Lewis Research Center:

The model that you have is quite similar to Thomas's replacement model, but you didn't mention it, or maybe you didn't even use it.

Sonin:

I know of Thomas's work.

Hendricks:

Ok, I think it is pretty good. To follow up on the other question; kinetic theory is still applicable here. I don't know how you can say that the vapor just slowly moves down; I think that is something you better take a look at. You should consider the fact that you do not have uniform condensation over the surface. If you did, you wouldn't have any turbulent eddies underneath the surface. You have cellular patterns underneath the surface. You are assuming that things are quiescent and they are not.

Sonin:

Where do you want me to start answering your questions at this point?

Hendricks:

You can start any place you want to, but you are going to have a tough time explaining that the surface is uniform when it is not.

Sonin:

We do not assume that the surface is uniform, nor, by the way, do I have a theory for this. The curve that I presented was purely empirical not theoretical. The surface is turbulent; the turbulence is imposed from the liquid side. The vapor does what it wants to arrive and condense onto the surface at the various points and times consistent with what goes on in the liquid as it removes the latent heat. I make no assumption about everything being absolutely static, but what I am saying is that it is the liquid side conditions which control the condensation rates; that is all that is concluded in this model. This modelling is an empirical modeling and not a theoretical one. Kinetic theory, of course, is always valid. I am familiar with kinetic theory, having taught it, but it has nothing to do with what happens at the liquid side. On the steam side, the steam is slowly drifting down to meet the interface and will condense there.

Hendricks:

I guess I would disagree with you there because kinetic theory is pretty explicate in that region, and it does predict the necessary condensation coefficients. You do have accommodation coefficients, you do have surface tension effects, you haven't considered damping in the surface due to surface tension, and I don't understand why you used the K-Epsilon model when a zero-order Prandtl model might be equally applicable. Why go to a two equation model for something which you don't know anything about?

Sonin:

The two equation model is not used for anything other than for a better idea to calibrate the system. It is not being used at all to characterize what happens at the interface. In fact, it can't be used because you can't really apply the boundary conditions for the K-Epsilon model at the free surface. There is no turbulence model for the free surface; what I am saying is that it is a useful crutch to predict what the turbulence is near the free surface, and you can apply this correlation to understand what the condensation rate is at the surface based on what the flow conditions are near it.

Hendricks:

Sounds to me that like you used the Prandtl model anyhow.

Sonin:

I haven't used the Prandtl model at all.

Hendricks:

It didn't sound to me like you used the K-Epsilon model in your description.

Sonin:

I didn't really describe what I did. If you want to talk about this later, I'd be perfectly happy to describe what we did theoretically, but we have no theory that applies to the condensation rate. As far as the kinetic theory is concerned, the only thing the kinetic theory does, as far as predicting the condensation rate, is to deal with the case when it is vaporside controlled, and it gives you an idea, for example, what, if any, Delta-T exists between the saturation temperature and the liquid temperature at the interface; it has nothing to do with the this problem.

Hendricks:

What is your guess as to how much you have to increase the surface area to account for the fact that you have a non-uniform surface, essentially due to the turbulence below?

Sonin:

The turbulence intensities were moderate for the tests presented. You could look at the surface and you could say the surface area is perturbed very little due to the turbulence. You could crank up the turbulence until you had big waves on the liquid surface, but that is not the conditions we looked at. The surface area did not change except when instability occurred. In that case, with the onset of the instability, the surface was more wavy, there was a higher degree of turbulence, and then the burst instability caused a roughing of the surface on a small, submilimeter scale. That also increased the surface area. That changed the whole process of condensation. Under the conditions we were looking at, with the exception of burst instabilities, the surface area was well characterized.