Review and Analysis of Condensation Experiments at UW-Madison

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Introduction

- Condensation of water vapor on cold/cryogenic surfaces is an important consideration for future fusion magnet designs
- Structural limitations may be an issue because of ice formation on the magnet systems
- An accurate assessment of the quantity of condensate/ice and subsequent loading to the magnet system is essential
- Experiments have been conducted (with analyses) at UW-Madison to determine the atmospheric moisture content effect on condensation rate and subsequent freezing on a stainless steel surface
- Modelling is utilized to determine frost conductance

Introduction

- Simple first principle models have been employed to test against preliminary experiments
- Test and Analysis sequence
 - Preliminary analyses performed (large ice formation rates seen)
 - Experiments Run
 - Determining ice properties (frost conductance i.e., h_{frost})
 - MELCOR simulations will be used when ice porosity is determined and code updated with ice properties as model parameters
- This presentation reviews the experiments and analysis performed

UW- Madison has been working in Fusion Safety over 20 yrs with our current activities focused on:

- Liquid metal compatibility tests with fusion blanket coolants
- Cryogenic liquid interactions (LHe, LN2) with water and structures
- Experimental analysis and MELCOR model development

- Simplified heat transfer model to determine ice production rate
- Heat conducted through stainless steel and frost layer, and then convected through the steam/gas mixture
- This heat removal rate drives ice formation
- Thickness of frost is changing with time
 - This is accounted for in the heat transfer equation
 - Added resistance via increase in frost layer
- Appropriate frost thicknesses and porosities will be matched to empirically determine a frost formation modeling methodology
- In the later stages, MELCOR will be utilized with its ice formation models to match the test data

Modeled as resistances in series (stainless, ice and steam/gas)

Heat transfer through material: Variables: $q=DT/[1/h_{steam/gas} + 1/h_{frost} + d_{ss}/k_{ss}]A$ A = surface areaCp = specific heat K = thermal conduc.Mass rate of ice produced: Dtime = time step DT = temp gradient $m_r = q/[DH_{vap} + DH_{fus} + Cp_{steam}DT_{steam} + Cp_{water}DT_{water}]$ H = heat transfer coeff r = densityDH = heat of formation Thickness of ice produced: Note: $h_{frost} \sim (1-porosity)^2 k_{ice}/d_{ice}$ thickness=[Dtime m_r]/[r_{ice} A]

- •With a known $h_{convection}$ we can eventually fit the test data to the model and determine the appropriate k_{ice} from the porosity of the ice
- Natural convection HTC (h_{convection})

Heat transfer coefficient = $k/[L Nu_1]$

Nu_L=0.54 Ra₁^{0.25}

 $Ra_L=gB[T_s-T_{inf}]L^3/[an]$

Variables

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Nu_L = nusselt number

Ra_L = Rayleigh number

L = length scale

K = thermal conductivity

g = gravity

B = 1/T_f

T_{bulk} = bulk temp

a = thermal diffusivity

n = viscosity
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•Representative value: $h_{convection} \sim 7 - 13 \text{ W/m}^2\text{-K}$ (small)

•Calculation of "gas" heat transfer coefficient (HTC)

- $h_{\text{steam/gas}}$ (total HTC)= h_{conv} + h_{cond}
- h_{conv} =0.13(k_g/L)Gr^{1/3}Pr^{1/3}
- h_{cond} =Sh[(D $h_{fg}CM_w$)/(LR_vT_iT_b)]F

Representative values:

$$h_{cond} \sim 47.9 \text{ W/m}^2\text{-K}$$
;
for $T_{boiler} = 81.5^{\circ}\text{C}$, $P_v = 0.5$, $P_{air} = 0.5$

$$h_{conv} \sim 8.9 \text{ W/m}^2\text{-K}$$
;
for $T_{boiler} = 81.5^{\circ}\text{C}$, $P_v = 0.5$, $P_{air} = 0.5$

$$\begin{array}{l} \mathsf{Pr} = \mathsf{C}_{\mathsf{p}}\mathsf{k}/\mathsf{m} \\ \mathsf{C} = \mathsf{P}/(\mathsf{RT}_{\mathsf{avg}}) \\ \mathsf{Sh} = 0.13(\mathsf{GrSc})^{1/3}\mathsf{F} \\ \mathsf{M}_{\mathsf{w}} = \mathsf{molecular} \ \mathsf{weight} \ \mathsf{H}_2\mathsf{O} \\ \mathsf{Sc} = \mathsf{m}/\mathsf{rD}_{\mathsf{o}} \\ \mathsf{R}_{\mathsf{v}} = 8314/18 \\ \mathsf{Gr} = \mathsf{gr}_{\mathsf{gb}}(\mathsf{r}_{\mathsf{gi}}\mathsf{-}\mathsf{r}_{\mathsf{gb}})\mathsf{L}^3/\mathsf{m}^2 \\ \mathsf{L} = \mathsf{length} \\ \mathsf{q} = \mathsf{ln}(\mathsf{R}\!+\!1)/\mathsf{R} \ \mathsf{Suction} \ \mathsf{term} \\ \mathsf{k}_{\mathsf{g}} = \mathsf{thermal} \ \mathsf{conduct.} \\ \mathsf{R} = (\mathsf{X}_{\mathsf{vi}}\mathsf{-}\mathsf{X}_{\mathsf{vb}})/(\mathsf{1}\!\cdot\!\mathsf{X}_{\mathsf{vi}}) \\ \mathsf{D} = \mathsf{diffusion} \ \mathsf{coeff.} \\ \mathsf{F} = \mathsf{ln}[\mathsf{X}_{\mathsf{nc},\mathsf{b}}/\mathsf{X}_{\mathsf{nc},\mathsf{i}}]/\mathsf{ln}[(\mathsf{1}\!\cdot\!\mathsf{X}_{\mathsf{nc},\mathsf{b}})/(\mathsf{1}\!\cdot\!\mathsf{X}_{\mathsf{nc},\mathsf{l}})] \\ \mathsf{X} = \mathsf{mole} \ \mathsf{fractions} \end{array}$$

• Plot of Ice Formation versus Time (no porosity)



• Ice formation rates are quite high (h_{condensation} drives ice formation)

Experimental Apparatus (Schematic)

• Schematic of vacuum vessel and stainless steel pedestal



Experimental Apparatus (photos)

Vacuum vessel with stainless steel condensation pedestal





Experimental Apparatus

• 316 SS Cryogenic Condensation structure with instrumentation (heat flux sensor, thermocouples)



Experimental Procedure

- Water vapor/air mixture is heated to desired conditions in the pressure tank (i.e., temperature/partial pressure)
- The vacuum test chamber is pumped down to a low (~ 200 mTorr) pressure
- Liquid nitrogen cools the stainless steel pedestal in the test volume, cooling the condensing surface to near 77 K
- When the stainless steel pedestal has reached an equilibrium thermal condition the gas is injected into the vacuum vessel
 A valve is opened on the pressure tank and the water vapor/air contents are slowly released into the vacuum test chamber
- The condensation/freezing event is filmed and data (temperatures, pressures and heat flux) are measured
- The system is allowed to reach pressure equilibrium

Initial Introduction of Gas

Test 7 Boiler at 81.5° C $P_v = 0.5$ bar $P_{air} = 0.5$ bar Plate at ~80 K



Preliminary Experimental Results

• Pedestal iced up after 81.5 C boiler experiment Pv = 0.5, Pair = 0.5



Preliminary Experimental Results



Pure Steam Injection

- The high heat transfer coefficient results in a sharp increase in plate temperature
- Uneven cooling of pedestal causes frost and clear ice together. The solid ice forms on the portion of the plate that is at a higher temperature.



Pure Steam Injection



Pure Steam Controlled injection

 Heavy ice formation after injection of pure water vapor from the boiler. The injection rate was controlled to main to keep a more uniform plate temperature.



Pure Steam Controlled injection



MELCOR Code

- Control-volume systems code for thermal-hydraulic analysis
 (SANDIA National Lab)
- Control volumes connected via orificed flow paths
- Experimental condensation/freezing rate can be modeled by MELCOR
- Benchmark the code against selected UW experiments
- Determine MELCOR utility in predicting ice formation on cryogenic structures used in fusion system designs

MELCOR Code

- MELCOR simulations have been run with "hard-wired" constant values for the ice thermal conductivity and porosity
- An updated version is being modified to allow easy input of these parameters
- Parametric analyses will be run with MELCOR utilizing various ice thermal conductivities and porosities
- This updated version of MELCOR will be used to match test results from the UW experiments
- Ice thermal conductivity and porosity will be varied to produce the desired output (i.e., matching the heat flux and temperatures from the experiment). This will be used to get the correct $h_{frost} = k_{frost}/d$.



- 1. Experiments were run to determine frost formation rates and heat fluxes on a cryo-cooled stainless steel pedestal in a vapor/air environment similar to accident conditions
- 2. First principle models were employed to determine characteristics of the frost formation on the cold structure
- 3. The model comparison to the test data will provide porosity behavior as a function of pressure and temperature for use in MELCOR for parametric analyses of the system design
- 4. MELCOR needs to be modified to allow easy input of these parameters to assist in comprehensive parametric analyses