Measurements of Critical Heat Flux using Mass Transfer System

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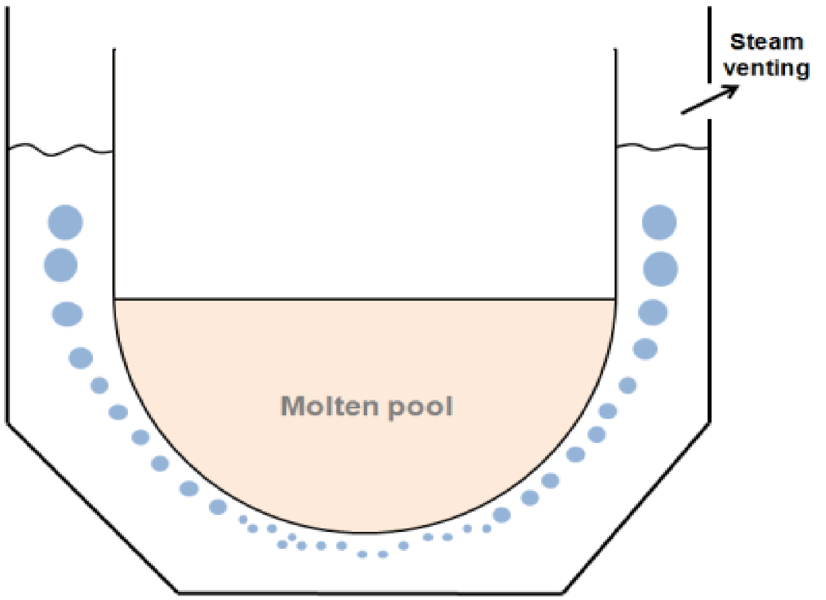
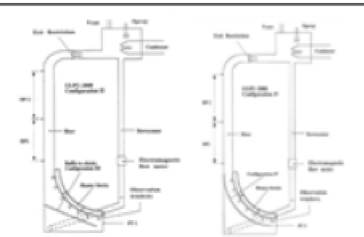
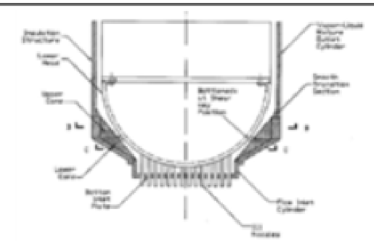
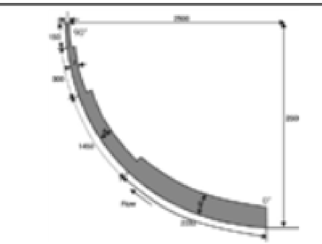
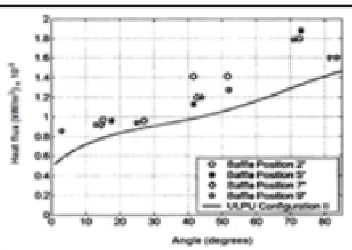
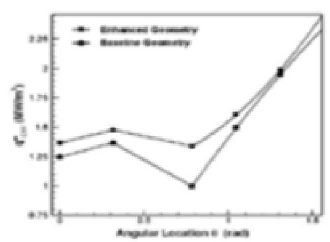
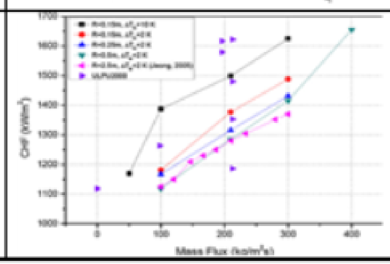
Introduction



- IVR-ERVC concept is one of the managements system in severe accident
- Critical Heat Flux(CHF) has been used to judge the safety on IVR-ERVC
- In this study, the CHF measured using mass transfer, and verified the results

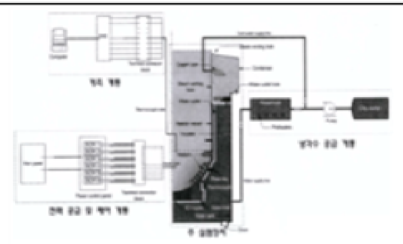
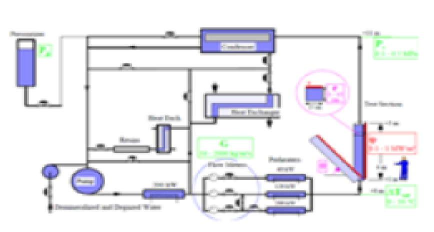
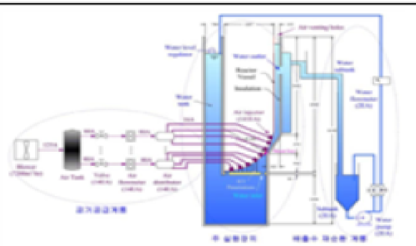
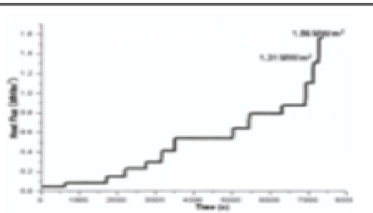
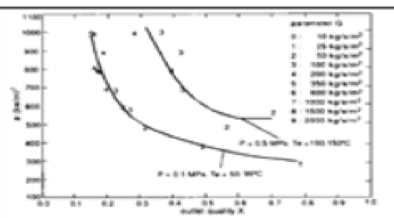
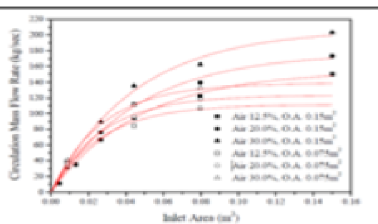
Theoretical background (1/4)

- IVR-ERVC

	ULPU	SBLB	KAIST
Information	University of California (2004)	Penn State University (2003)	KAIST (2005)
Purpose	Measurement CHF with Insulation geometry and Gap size on various nuclear reactor vessel condition	Measurement CHF with Insulation geometry on Subcooling, surface coating condition,	Mass flux, Exit quality, Subcooling Effect for CHF
Scaling analysis	1/1 (AP600, AP1000)	1/20 (APR1400) Experimental apparatus – Linear Scale down Gap size - F.B. Cheung Scale down	1/1, 1/5, 1/10, 1/16 (APR1400) Experimental apparatus – Linear Scale down Gap size - F.B. Cheung Scale down
Heat source	Heater	Cartridge heater	Electric current
Heat flux	Main heat source – CHF Sub heat source - Maximum heat flux without CHF	Maximum heat flux : 1.8 MW/m^2	Various 4 heat flux by difference thickness of heat source (Max for metal layer)
Measurement Position	Specific angle	Specific angle	Metal layer
Experimental apparatus			
Experimental results			

Theoretical background (2/4)

- IVR-ERVC

	CASA-SC	SULTAN	T-HERMES
Information	Seoul National University (2012)	France CEA (1998)	KAERI (2005)
Purpose	Effect of Shear Key and ICI nozzle on CHF Measurements	Measurements CHF on various Mass flow rate, heat flux, Gap size, Angle Verification of CATHARE (Two-phase flow numerical code)	T-HERMES-HALF : Various entrance surface size and aeration rate T-HERMES-SMALL : a preparatory experiments for T-HERMES-HALF
Scaling analysis	1/10 (APR1400) Experimental apparatus – Ishii Scale down Gap size - F.B. Cheung Scale down	Experimental apparatus - Full scale	SMALL – 1/2, HALF – 1/21.6 (APR1400) Experimental apparatus – Linear Scale down Gap size - F.B. Cheung Scale down
Heat source	Electric current	Electric current	Electric current
Heat flux	Metal layer : 2.5 MW/m^2 Oxide layer : 1.2 MW/m^2	Only one side In a square duct $0.3 MW/m^2$-$1.0 MW/m^2$	T-HERMES – SMALL : Average heat flux - 173 kW/m^2 T-HERMES-HALF : none
Measurement Position	Metal layer	In a square duct	T-HERMES-SMALL : Metal layer T-HERMES-HALF : Entrance mass flow rate
Experimental apparatus			
Experimental results			

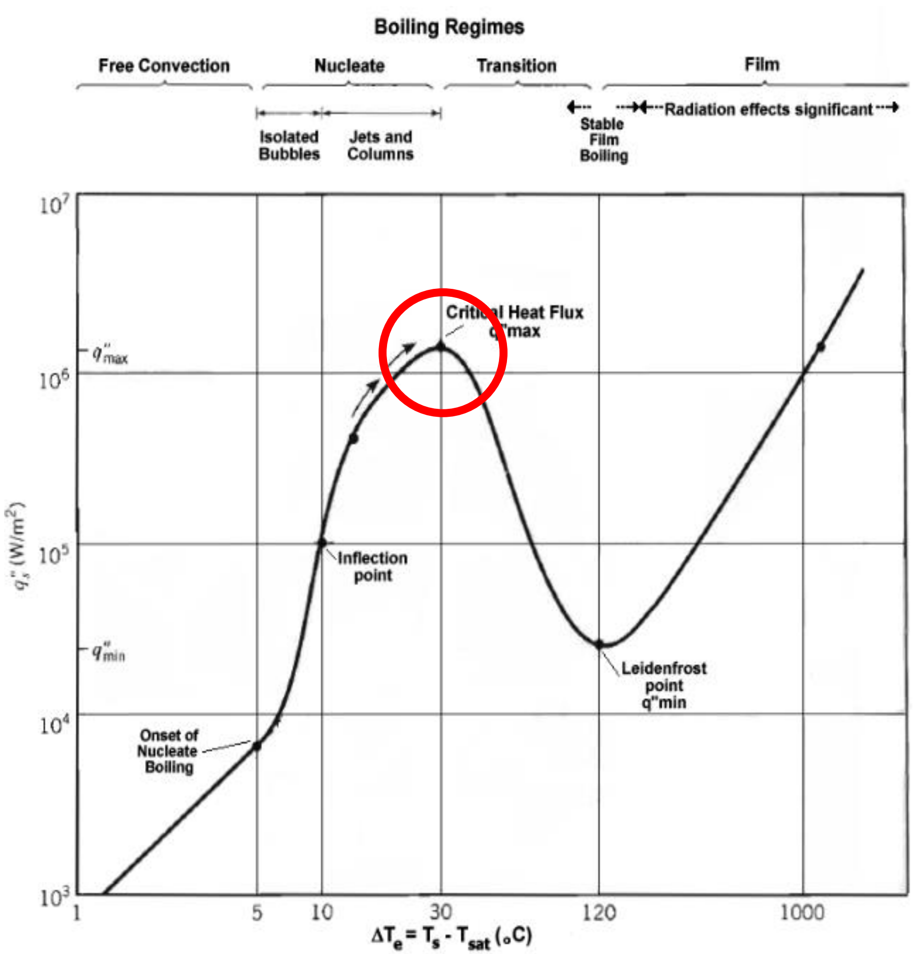
Theoretical background (3/4)

- Critical Heat Flux

Nucleate boiling

Film boiling

Theoretical background (4/4)



- Critical heat flux(CHF)

⇒ Maximum point of Heat flux

⇒ Generating point of Film boiling

⇒ Index for evaluating the structural safety

DNB, Dryout, Burnout, Boiling crisis, Boili

transition etc.

Experimental Methodology

- Mass transfer in a cupric acid-copper sulfate

  : Electric migration ⇒ N_m → – None reaction in mass transfer

  : Diffusion ⇒ N_d

  : Convection ⇒ N_c

$$N_m = \frac{t_n I_{lim}}{nF}$$

- Mass transfer flux

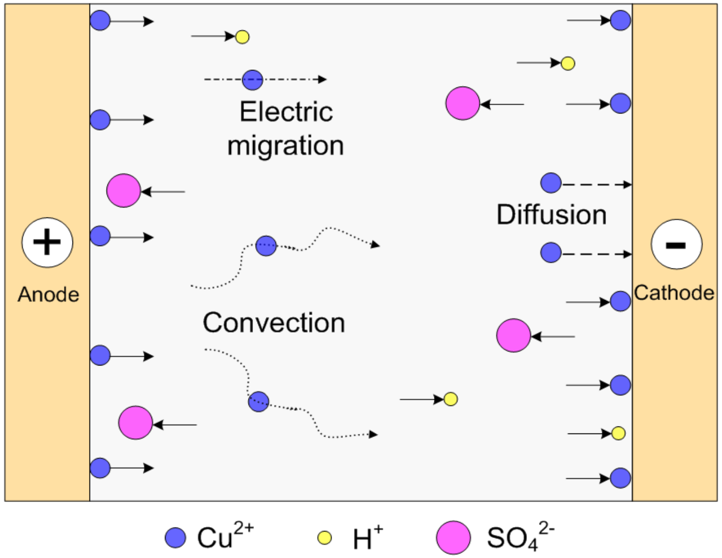
  : Total mass transfer flux

$$N_t - N_m = N_d + N_c = \frac{(1-t_n)I_{lim}}{nF} = h_m(C_b - C_s)$$

⇒ **Mass transfer coefficient**

$$h_m = \frac{(1-t_n)I_{lim}}{nF(C_b - C_s)}$$

→ **C_s** can be regarded as 0 by measuring limiting current



Experimental Methodology

- Governing equations

Heat transfer	Mass transfer
$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0$	
$\rho\frac{Du}{Dt}=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+X$	
$\frac{DT}{Dt}=\alpha\nabla^2 T$	$\frac{DC}{Dt}=D\nabla^2 C$

- Dimensionless numbers

Heat transfer	Mass transfer
$Nu=\frac{h_h L}{k}$	$Sh=\frac{h_m L}{D_m}$
$Pr=\frac{\nu}{\alpha}$	$Sc=\frac{\nu}{D_m}$
$Ra=\frac{g\beta\Delta T L^3}{\alpha\nu}$	$Ra=\frac{gL^3}{D\nu}\frac{\Delta\rho}{\rho}$

- Analogy concept

Heat transfer problem ⇨ Mass transfer problem

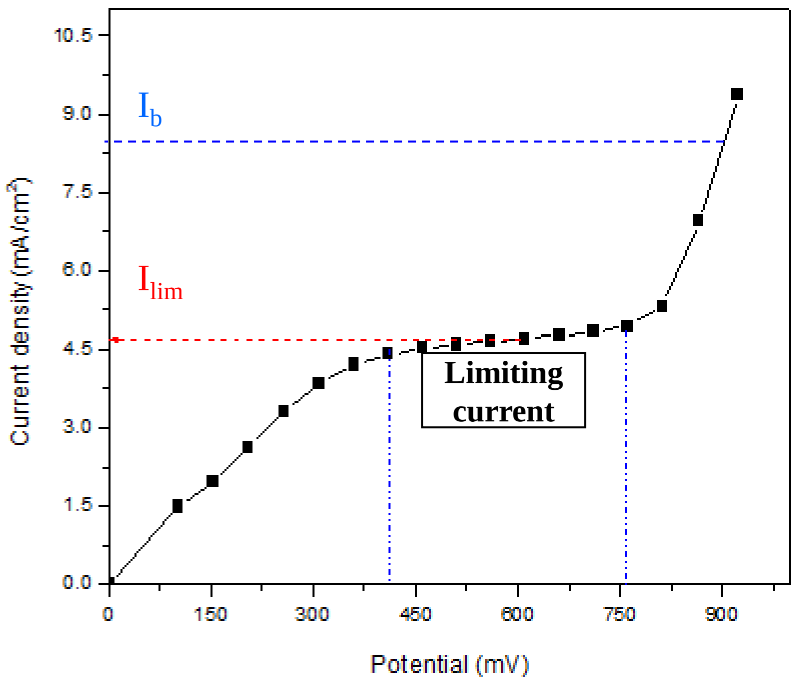
Analogy

Mass transfer problem ⇩ Mass transfer solution

Heat transfer solution ⇦ Mass transfer solution

Experimental Methodology

- Copper Electroplating System



Current change according to voltage growth

1) Limiting current region, Concentration of electrode surface 0, Calculating mass transfer coefficient

   $(I_{lim} = Limiting\ current\ \Rightarrow sensible\ heat\ transfer)$

2) Hydrogen ion alert to hydrogen vapor as getting the activation energy

   $(I_b = boiling\ current \Rightarrow latent\ heat\ transfer)$

$$2H_3O^+ + 2e^- \rightarrow H_2 + 2H_2O$$

Experiments – Open channel system

- Purpose
  - : CHF measurement in open channel system by mass transfer system
  - : Heater size, heater component, angle dependent.

- Methods
  - : Single electrode was used
  - : Galvanostatic method was adopted

- Test matrix

Prandtl number	*Length* (m)	*Width* (m)	Angle (*Θ*)	Metal
2,014	0.010, 0.020	0.010, 0.020	0°, 30°, 45°, 60°, 90°, 180°	Copper, Aluminum, Statinless steel, Brass

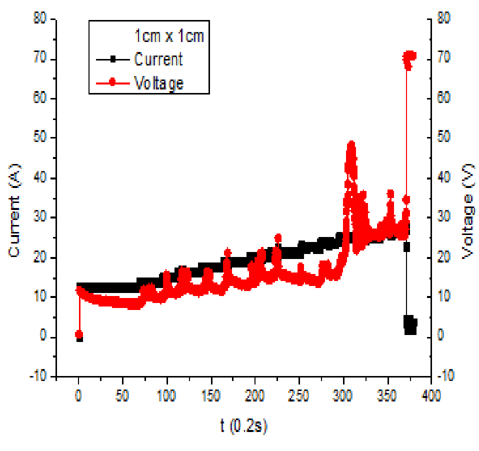
Experiments – Open channel system

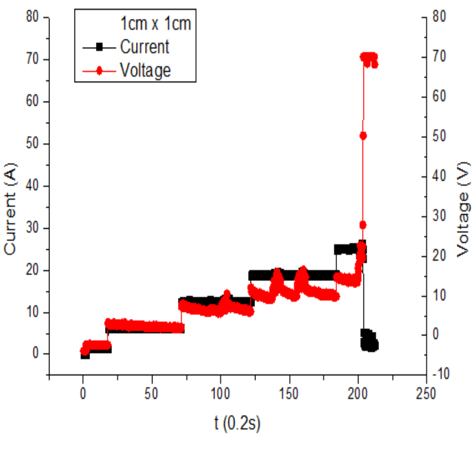
Measurements of CHF on upward facing plate in Mass transfer

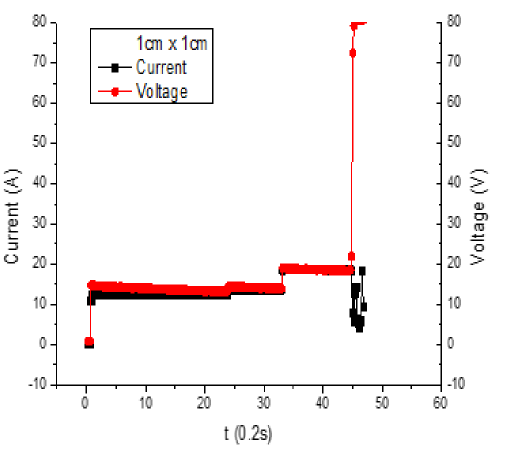
: Drastic increase region of voltage according to current

: Increasing current ⇒ Finding the drastic differ region of voltage

⇒ Measuring Current ⇒ Transfer as heat flux using current







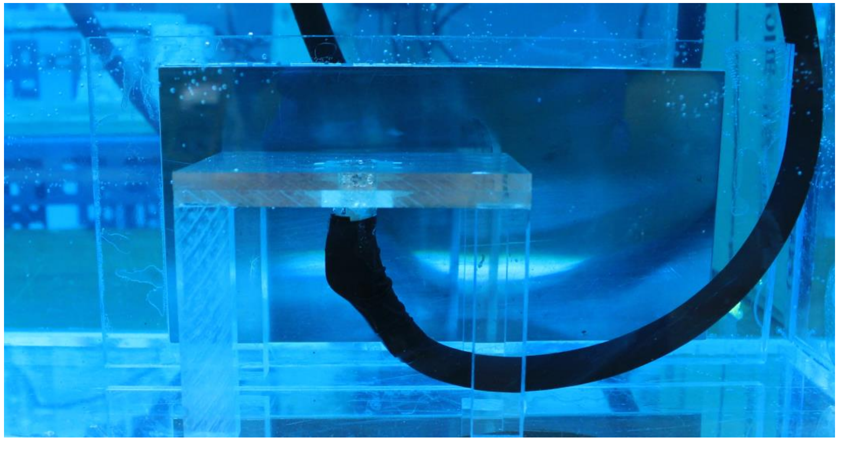
Experiments – Open channel system

1. Power supply – SGI 100A/150V(15kW)
2. Data Acquisition – Agilent 34972A
3. Electrodes

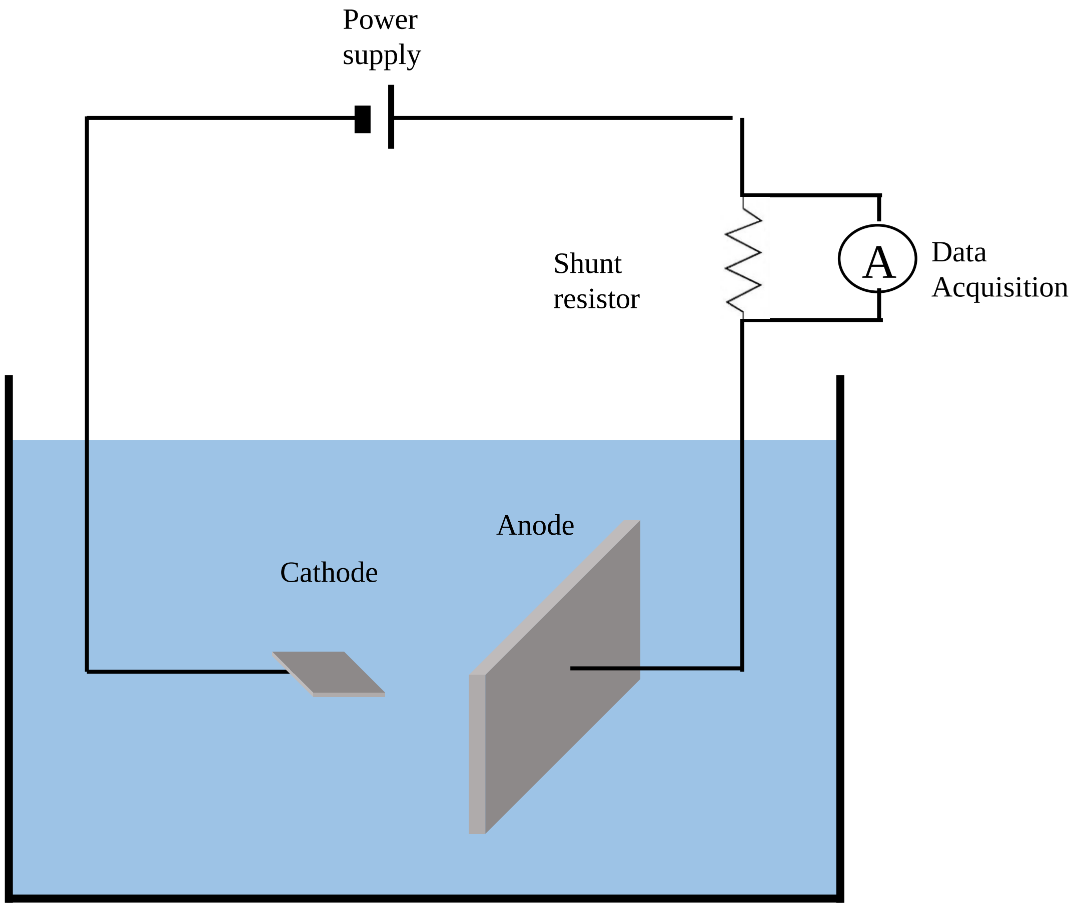
   : Cathode(0.01m x 0.01m, 0.02m x 0.02m), Anode(0.1m x 0.2m)
4. Working fluid

   : Sulfuric acid and copper sulfate

   : $CuSO_4 = 1.5M$, $H_2SO_4 = 0.05M$



Experiments – Test circuit



CHF correlation in Mass transfer

- Process of heat flux calculation.

1) Calculate amount of H_2 as unit time and unit area

$$\frac{\mathrm{I_b}}{\mathrm{nF}} = (kmole/\, m^2 \cdot s) = (\text{Hydrogen atom deoxidization mole} \,/\, m^2 \cdot s)$$

2) Using the latent heat of water $2247.63(J/g)$

3) The energy for generating hydrogen bubble in the solution

$$\frac{\mathrm{I_b}}{\mathrm{2F}} \times 18(g/mole) \times 2247.63(J/g) \times \sqrt{\frac{\rho_{H_2O}}{\rho_{H_2}}} = \mathrm{q}''$$

Theory – determine the heater size

- Critical wavelength(λ_c) is determined to minimum plate size for measurements CHF

$$\lambda_c = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$

- Five times of most dangerous wavelength(λ_d) was used for determining minimum plate size as not to be affected with plate size.

$$\lambda_d = \lambda_c\sqrt{3} = \sqrt{\frac{3\sigma}{g(\rho_l - \rho_v)}}$$

- To apply for the mass transfer experiments using Sulfuric acid and copper sulfate, the λ_d is 0.7mm thus Minimum plate size is over 3.5 mm.

Experiments – determine the heater size

- Identify the heater size as experiments
  - Using various plate size as 1 cm×1 cm, 2 cm×2 cm
  - Current density and CHF are much similar

Heater size	Results of current (A)	Current density (A/m^2)	CHF(W/m^2)
1 cm×1 cm	18 A	180000	101.46
2 cm×2 cm	66 A	170000	95.82

Experiments – determine the heater component

- Identify the heater component as experiments
  - Using various metal as copper, Aluminum, Stainless steel, Brass
  - The Aluminum is optimal metal for experiments

	CHF (kW/m^2)	Copper eduction	Copper wipe	Suitability
Copper	107.15	many	bad	2
Aluminum	101.5	few	good	1
Stainless steel	112.8	many	good	3
Brass	-	many	bad	3

CHF correlation in Heat transfer

- Zuber correlation has been used to predict the CHF

$$q''_{CHF} = C\ h_{fg}\ \rho_v^{1/2}[g\sigma(\rho_l - \rho_v)]^{1/4}$$

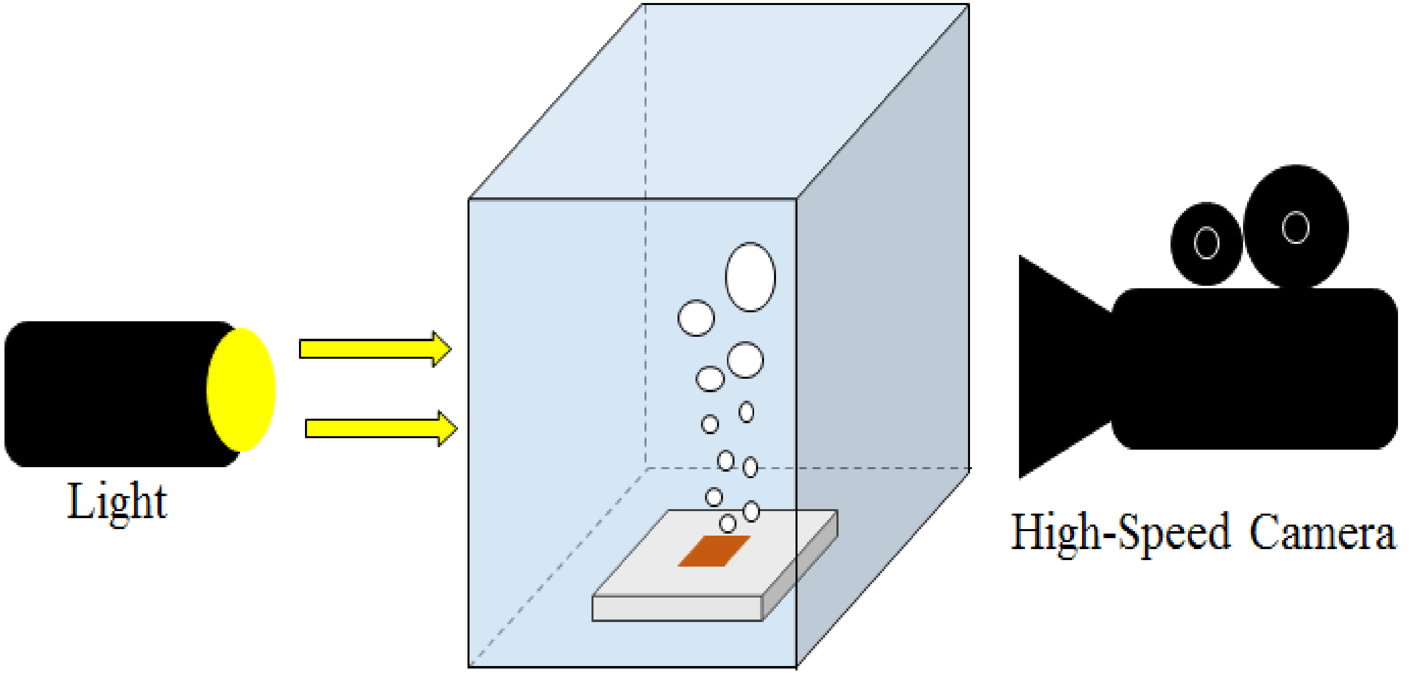
  - $C = 0.149$ *(Horizontal flat plate)*
  - $h_{fg} = Latent\ heat$
  - $g = Gravitiational\ acceleration$
  - $\sigma = \ Surface\ tension$
  - $\rho_l = Density\ for\ liquid$
  - $\rho_v = Density\ for\ vapor$

Results - Heat transfer v.s Mass transfer

	Heat transfer	Mass transfer Experiment
CHF(kW/m^2)	1253.1	169.1
Initial Temperature(℃)	100	22
Final Temperature(℃)	100	-
Liquid density (kg/m^3)	957.9	1096.56
Vapor density (kg/m^3)	0.5956	0.0813
Surface tension (N/m)	58.9×10^{-3}	72.0×10^{-3}
Gravity(m/s^2)	9.8	
Constant number	0.149	
Latent heat(J/g)	2247.63	2449
Products	H_2O	H_2
Methods	Phase change	Electrochemical reaction
Reaction formula	-	$2H_3O^+ + 2e^- \rightarrow H_2 + 2H_2O$
Mass condition	2 Phase	2 Component

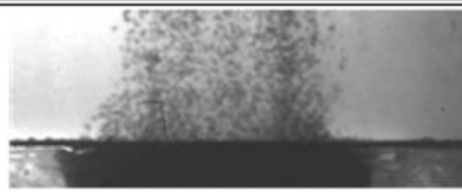
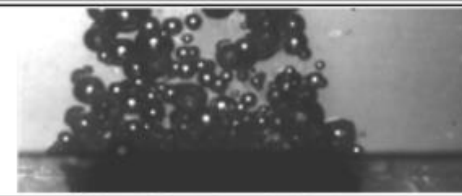
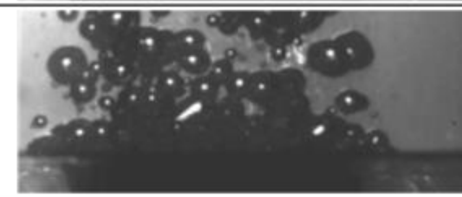
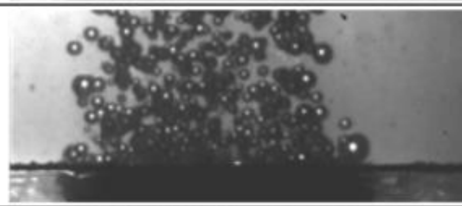
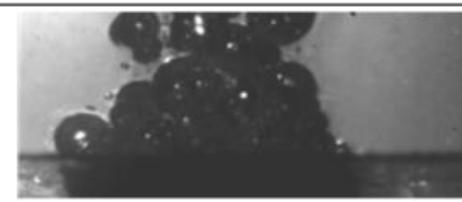
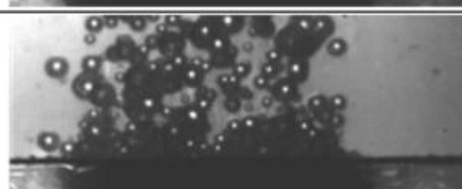
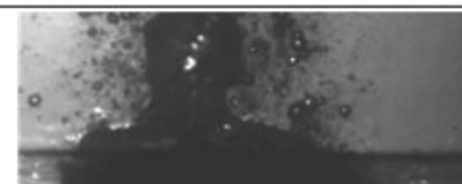
Experiments – Visualization

- Visualization using High-speed camera



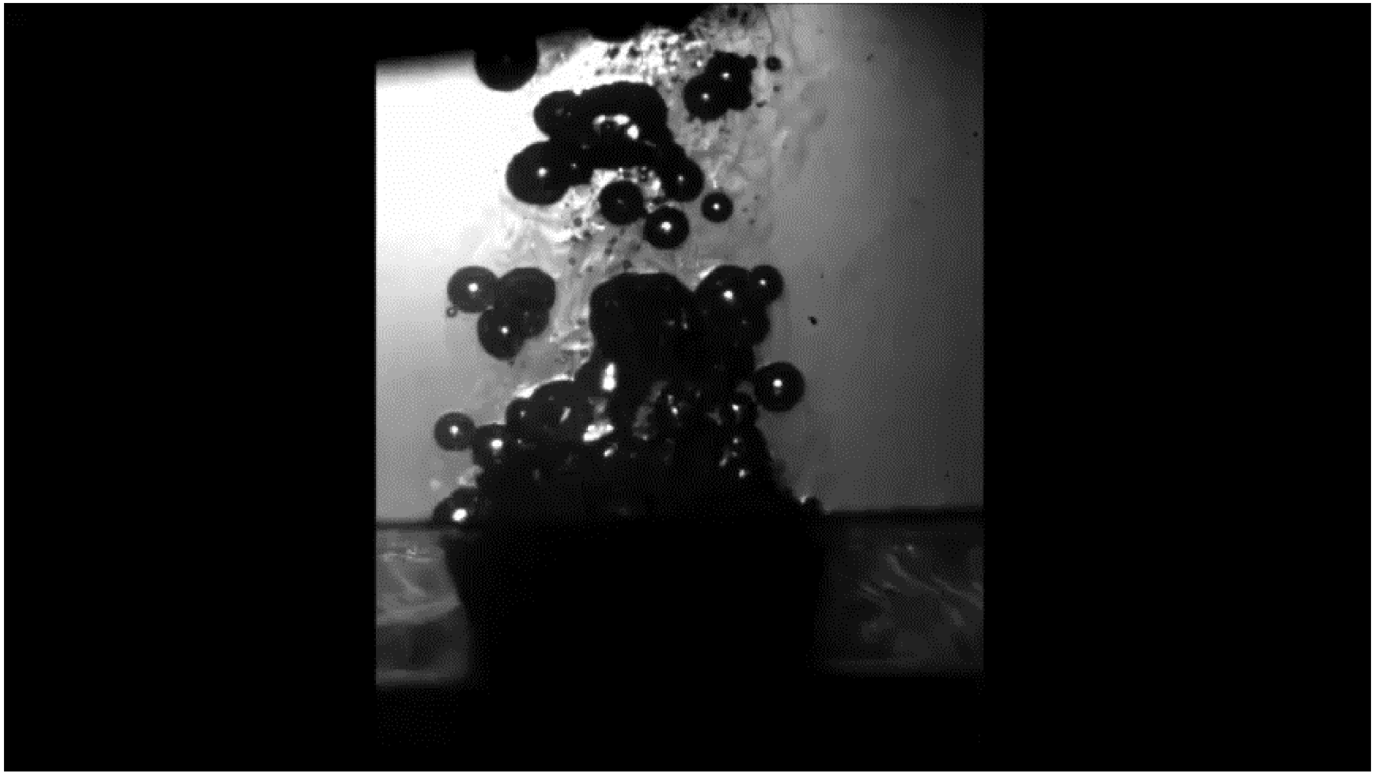
Experiments results – Visualization

- Visualization results – still cut

Current(A)	Still cut	Current(A)	Still cut
0.1		15.0	
1.0		20.0	
5.0		25.0	
10.0		25.0 (CHF)	

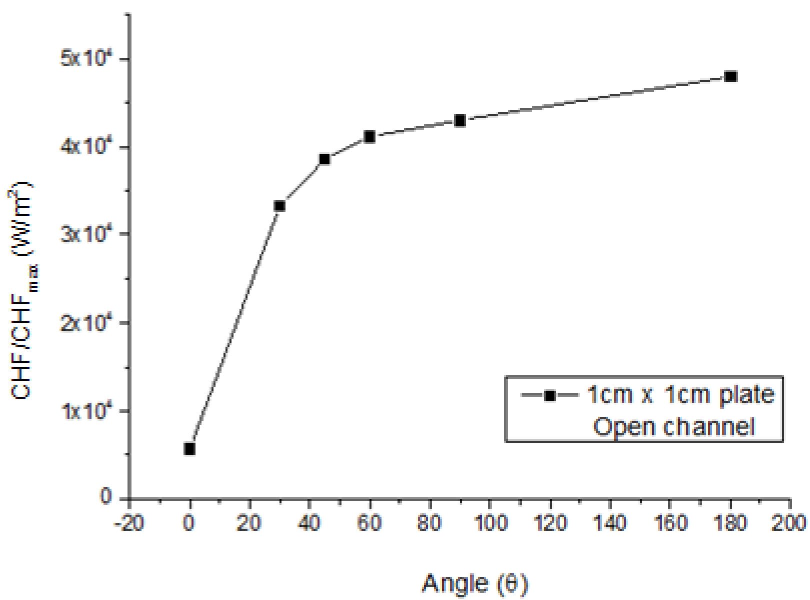
Experiments results – Visualization

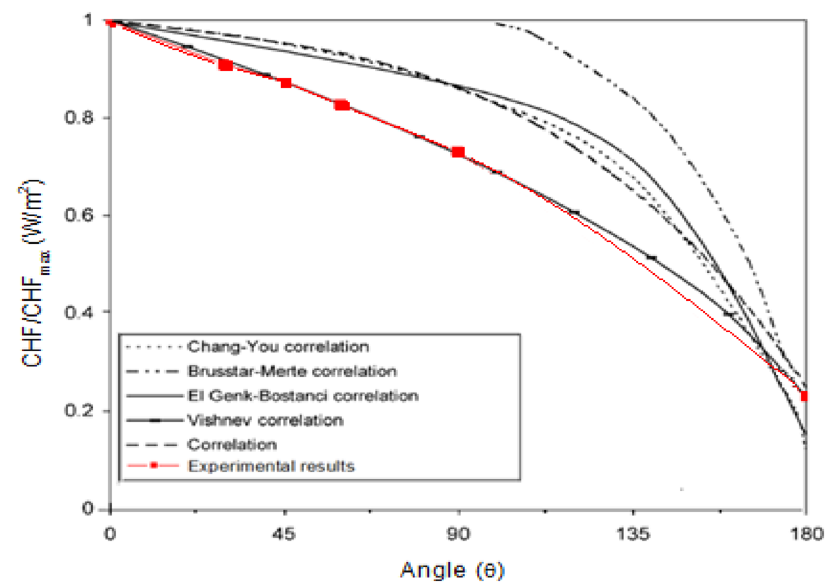
- Visualization results – CHF



Experiments results – Angle dependent

- CHF measurements on downward facing plate
  - CHF improved according to angle increase.
  - Comparison with existing correlation





Conclusions

- Critical heat flux can be measured using mass transfer methodology.
- The hydrogen bubble from the electro plate in mass transfer system are combined to be film boiling such as heat transfer CHF mechanism.
- Between heat and mass transfer results are much similar in relative value because the CHF mechanism are same.
- The mass transfer experimental apparatus and condition is very simple than heat transfer.

Thank you for your attention.