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APPENDICES

Appendix A Parameters of Hydrogen Accumulation Loop

Table A1 Volume of accumulation loop

Components	Volume (cm^3)	Method
Pressure transducer	1.5	Supplier
Valve	0.8	Suppler
VCR Tee	1.32	Calculated
Silver tubing (1/3 outside furnace)	7.54	Calculated
VCR blind fitting	0.11	Calculated
Cup 1	0.297	Calculated
Cup 2	0.185	Calculated
Cup 3	2.07	Calculated
Cup 4	1.76	Calculated
Cup 5	0.297	Calculated
Cup 6	0.185	Calculated
Cup 7	2.07	Calculated
Cup 8	1.76	Calculated

Table A2 Parameters of cups

Component	Outer Diameter (m)	Perimeter of the Cup on the Tube Surface (m)	Surface Area of Pipe under the Cup (m^2)
Cup 1	6.35×10^{-3}	0.0200	8.025×10^{-5}
Cup 2	6.35×10^{-3}	0.0200	7.391×10^{-5}
Cup 3	12.70×10^{-3}	0.0399	2.129×10^{-4}
Cup 4	12.70×10^{-3}	0.0399	2.025×10^{-4}
Cup 5	6.35×10^{-3}	0.0200	8.025×10^{-5}
Cup 6	6.35×10^{-3}	0.0200	7.391×10^{-5}
Cup 7	12.70×10^{-3}	0.0399	2.129×10^{-4}
Cup 8	12.70×10^{-3}	0.0399	2.025×10^{-4}

Appendix B Calculations of Surface Area of Pipe under the Cup, Cup Volume, Cup Perimeter, Surface Area of Cup inside the Cup, and Mean Temperature

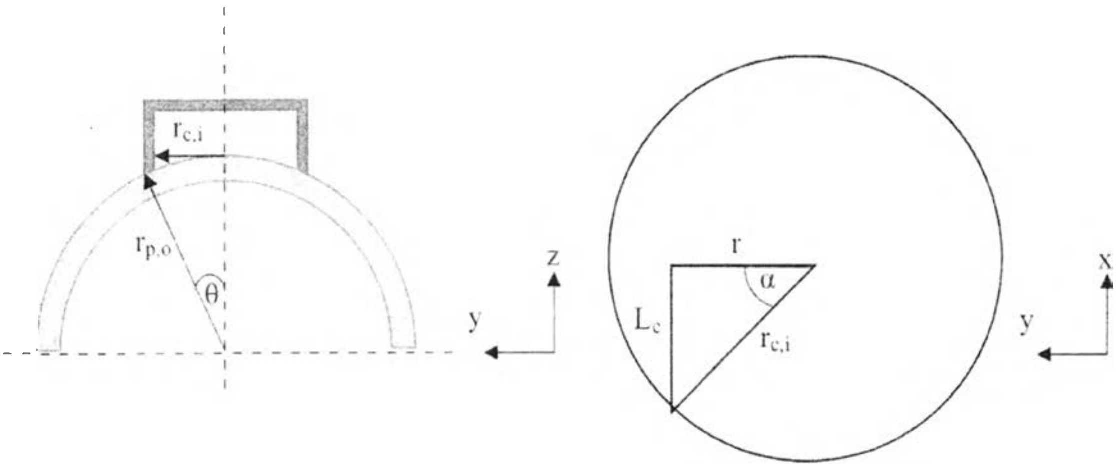

Figure B1 Schematic of cup mounted on a carbon steel pipe for the calculation of surface area under the cup.

The surface area of pipe under the cup was determined based on the outer diameter of pipe as shown in Equation B.1 where a quarter if the geometry is considered due to symmetry. The surface area of pipe under the cup is, thus, four times this integration.

$$A = \int_0^{\sin^{-1}\left(\frac{r}{r_{p,o}}\right)} L_c r_{p,o} \, d\theta \qquad (B.1)$$

where

A = outer surface area of pipe which is under the cup (m^2)

$r_{c,i}$ = inner radius of cup (m)

$r_{p,o}$ = outer radius of pipe (m)

L_c = length around the edge of the cup as a function of α (m)

r = radius direction (m)

The length around the edge of the cup as a function of α, L_c, can be determined from Equation B.2 where α was found as a function of θ through Equations B.3-B.5.

$$L_c = r_{c,i} \sin\alpha \qquad (B.2)$$

$$\sin\theta = \frac{r}{r_{p,o}} \tag{B.3}$$

$$\cos\alpha = \frac{r}{r_{c,i}} \tag{B.4}$$

$$\alpha = \cos^{-1}\left(\frac{r_{p,o}\sin\theta}{r_{c,i}}\right) \tag{B.5}$$

Therefore, Equation B.1 becomes as Equation B.6:

$$A = \int_0^{\sin^{-1}\left(\frac{r_{c,i}}{r_{p,o}}\right)} r_{p,o} r_{c,i} \sin\left(\cos^{-1}\left(\frac{r_{p,o}\sin\theta}{r_{c,i}}\right)\right) d\theta \tag{B.6}$$

The volume of cup (V_{cup}) was calculated by the summation of cylindrical cup volume based on the minimum height of the cup ($V_{cup,min}$) and the remaining element volume of the cup ($V_{element}$).

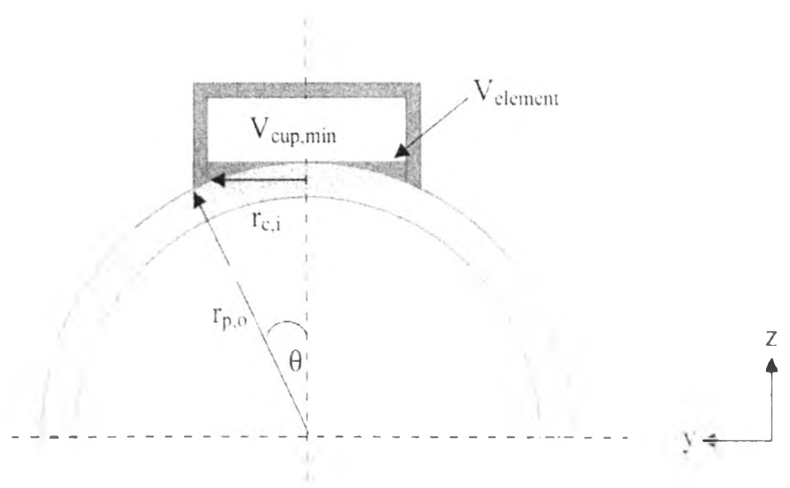

Figure B2 Schematic of cup mounted on a carbon steel pipe showing the breakdown of the cup volume.

The volume of element ($V_{element}$) is the product of the length, the height and the width of the element based on a quarter of the geometry which are shown in Equations B.7-B.9.

Length of element: $r_{c,i}\sin\alpha$ (B.7)

Height of element: $$r_{p,o} - \sqrt{r_{p,o}^2 - r^2} \qquad \text{(B.8)}$$

Width of element: $$dr \qquad \text{(B.9)}$$

Therefore, $$dv = \left(r_{c,i}\sin\alpha\right)\left(r_{p,o} - \sqrt{r_{p,o}^2 - r^2}\right)dr \qquad \text{(B.10)}$$

In order to solve Equation B.10, α must be determined as a function of r which is already defined as shown in Equation B.4. The volume of element and cup volume are, thus, as in Equations B.11-B.12.

$$V_{element} = \int_0^{r_{c,i}} \left(r_{p,o} - \sqrt{r_{p,o}^2 - r^2}\right)\left(r_{c,i}\sin\left(\cos^{-1}\frac{r}{r_{c,i}}\right)\right)dr \qquad \text{(B.11)}$$

$$V_{cup} = V_{cup\ min} + 4V_{element} \qquad \text{(B.12)}$$

where

$V_{element}$ = remaining element volume of the cup (m^3)

V_{cup} = cup volume (m^3)

$V_{cup\ min}$ = cylindrical cup volume based on the minimum height of the cup (m^3)

The perimeter of cup can be determined from Equation B.13 where a quarter of the geometry is considers due to symmetry. The cup perimeter is thus four times this integration.

$$p_c = \int_0^{\frac{\pi}{2}} s\,d\theta \qquad \text{(B.13)}$$

where

p_c = perimeter of cup (m)

s = distance between the center of cup and edge of cup (m) as shown in Figure B.3 which can be calculated from Equation B.14 which a and B can be solved be Equations B.15 and B.16.

$$s^2 = a^2 + r_{c,o}^2 \qquad \text{(B.14)}$$

where

$$a = \sqrt{r_{p,o}^2 - B^2} - \sqrt{r_{p,o}^2 - r_{c,o}^2} \qquad \text{(B.15)}$$

and

$$B = r_{c,o}\cos\theta \qquad \text{(B.16)}$$

where

$r_{c,o}$ = outer radius of cup (m)

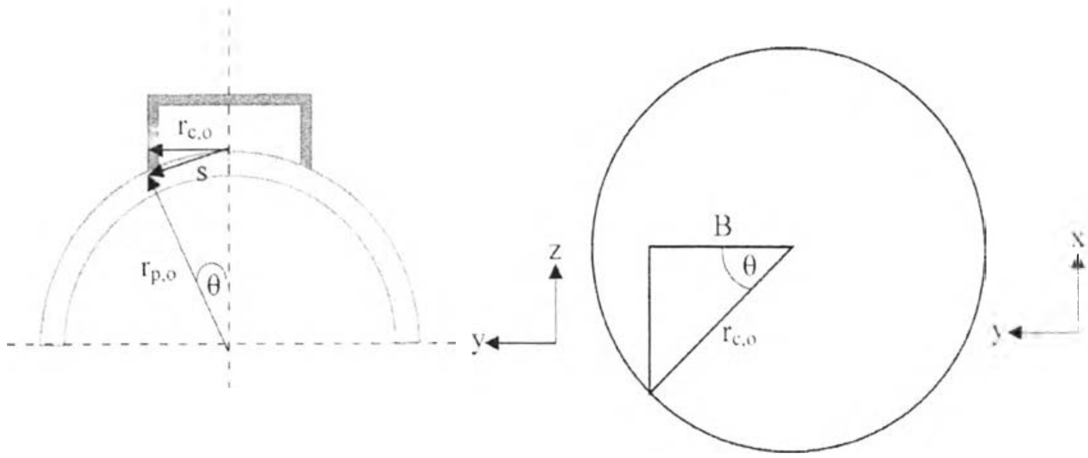

Figure B3 Schematic of cup mounted on a carbon steel pipe for the calculation of the perimeter of the cup.

Therefore, Equation B.13 becomes as Equation B.17.

$$p_c = \int_0^{\frac{\pi}{2}} \left(r_{c,o}^2 + \left(\sqrt{r_{p,o}^2 - r_{c,o}^2 \cos^2 \theta} - \sqrt{r_{p,o}^2 - r_{c,o}^2} \right)^2 \right)^{1/2} d\theta \qquad \text{(B.17)}$$

The surface area of cup inside the cup can be determined by Equation B.18 where a quarter of geometry is considered due to the symmetry. Consequently, the surface area of side wall inside the cup is four times this integration.

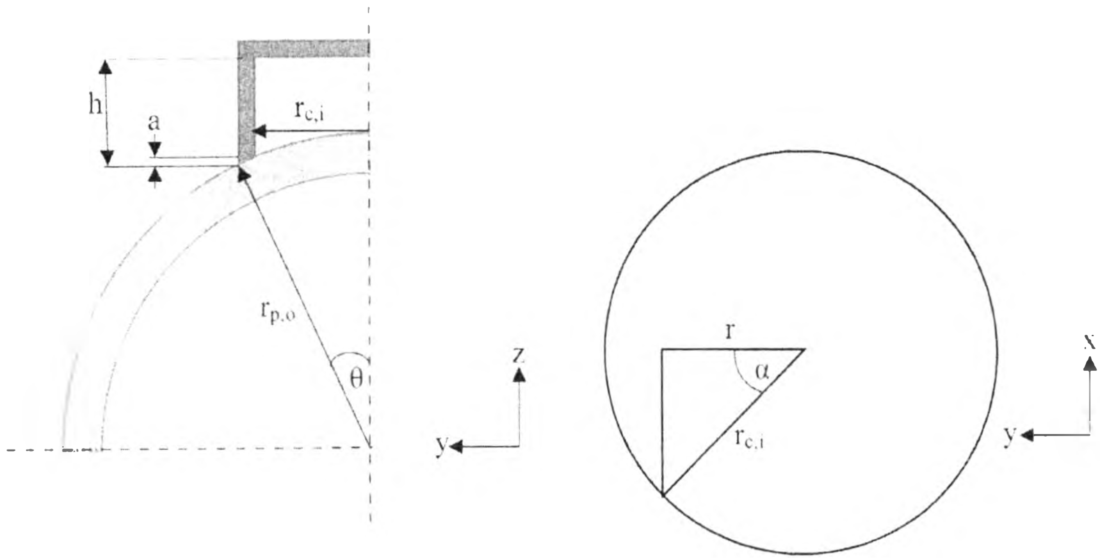

Figure B4 Schematic of cup mounted on a carbon steel pipe for the calculation of surface area of cup inside the cup.

$$A_c = \int_0^{\frac{\pi}{2}} (h-a) r_{c,i} \, d\alpha \qquad \text{(B.18)}$$

where

A_c = surface area of cup inside the cup (m^2)

h = height of cup (m)

a = height of element (m)

Equation B.18 shows that the surface area of cup inside the cup is based on the height of cylindrical element which can be calculated from the height of element (a) and height of cup as shown in Equation B.19 where a and r can be calculated from Equations B.20 and B.21.

Height of cylindrical element: h – a (B.19)

where

$$a = \sqrt{r_{p,o}^2 - r^2} - \sqrt{r_{p,o}^2 - r_{c,i}^2} \qquad \text{(B.20)}$$

and

$$r = r_{c,i} \cos\alpha \qquad \text{(B.21)}$$

Therefore, Equation B.18 becomes Equation Equation B.22.

$$A_c = \int_0^{\frac{\pi}{2}} \left[h - \left(\sqrt{r_{p,o}^2 - (r_{c,i} \cos\alpha)^2} - \sqrt{r_{p,o}^2 - r_{c,i}^2} \right) \right] r_{c,i} d\alpha \tag{B.22}$$

The above integrals were solved numerically.

For inner height (h_{in}) can be calculated by Equation B.23.

$$h_{in} = h - \left(\sqrt{r_{p,o}^2 - r_{c,i}^2} - \sqrt{r_{p,o}^2 - r_{c,o}^2} \right) \tag{B.23}$$

For mean temperature calculation, the ideal gas law is used as shown in Equation B.24-B.25, but due to the configuration of the test apparatus as shown in Figure 3.1, some parts of the hydrogen containing volume consisting of pressure transducers, valves, VCR tees, VCR blind fittings and one-third of silver tubing are outside the furnace. The mean temperature is, then, calculated by based on the volume of hydrogen at a given temperature for components that are inside and outside the furnace as shown in Equation B.26-B.28.

Ideal gas law: $$PV = nRT \tag{B.24}$$

$$n = \frac{PV}{RT} = \frac{P}{R} \times \frac{V}{T_{mean}} \tag{B.25}$$

So, $$n_t = n_{in} + n_{out} \tag{B.26}$$

Then, $$\frac{V}{T_{mean}} = \frac{V_{in}}{T_{in}} + \frac{V_{out}}{T_{out}} \tag{B.27}$$

Therefore, $$T_{mean} = \frac{V}{\frac{V_{in}}{T_{in}} + \frac{V_{out}}{T_{out}}} \tag{B.28}$$

where

n_t = total moles hydrogen gas (mole)

n_{in} = number of moles of hydrogen gas accumulated in the components which are inside the furnace (mole)

n_{out} = number of moles of hydrogen gas accumulated in the components which are outside the furnace (mole)

T_{mean} = absolute mean temperature (K)

V = total hydrogen gas volume (m^3)

V_{in} = hydrogen gas volume accumulated in the components which are inside the furnace (m^3)

V_{out} = hydrogen gas volume accumulated in the components which are outside the furnace (m^3)

Although the temperature may vary to some degree along the length of the silver tubing which has one-third of the length outside the furnace, the total volume of silver tubing is minimal so it is assumed that the hydrogen within this volume has a constant temperature gradient.

Appendix C Parameters of Hydrogen Accumulation Loop after Redesign of the Cups

Table C1 Volume of accumulation loop when the cups were redesigned

Components	Volume (cm^3)	Method
Pressure transducer	1.5	Supplier
Valve	0.8	Suppler
VCR Tee	1.32	Calculated
Silver tubing (1/3 outside furnace)	7.54	Calculated
VCR blind fitting	0.235	Calculated
Cup 1	0.119	Calculated
Cup 2	0.119	Calculated
Cup 3	0.267	Calculated
Cup 4	0.267	Calculated
Cup 5	0.119	Calculated
Cup 6	0.119	Calculated
Cup 7	0.267	Calculated
Cup 8	0.267	Calculated

Table C2 Parameters of new cups

Component	Outer Diameter (m)	Perimeter of the Cup on the Tube Surface (m)	Surface Area of Pipe under the Cup (m^2)
Cup 1	21×10^{-3}	0.0660	2.409×10^{-4}
Cup 2	23×10^{-3}	0.0723	2.692×10^{-4}
Cup 3	23×10^{-3}	0.0723	2.992×10^{-4}
Cup 4	25×10^{-3}	0.0786	3.307×10^{-4}
Cup 5	11×10^{-3}	0.0346	1.228×10^{-4}
Cup 6	21×10^{-3}	0.0660	2.409×10^{-4}
Cup 7	13×10^{-3}	0.0409	1.653×10^{-4}
Cup 8	23×10^{-3}	0.0723	2.992×10^{-4}

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