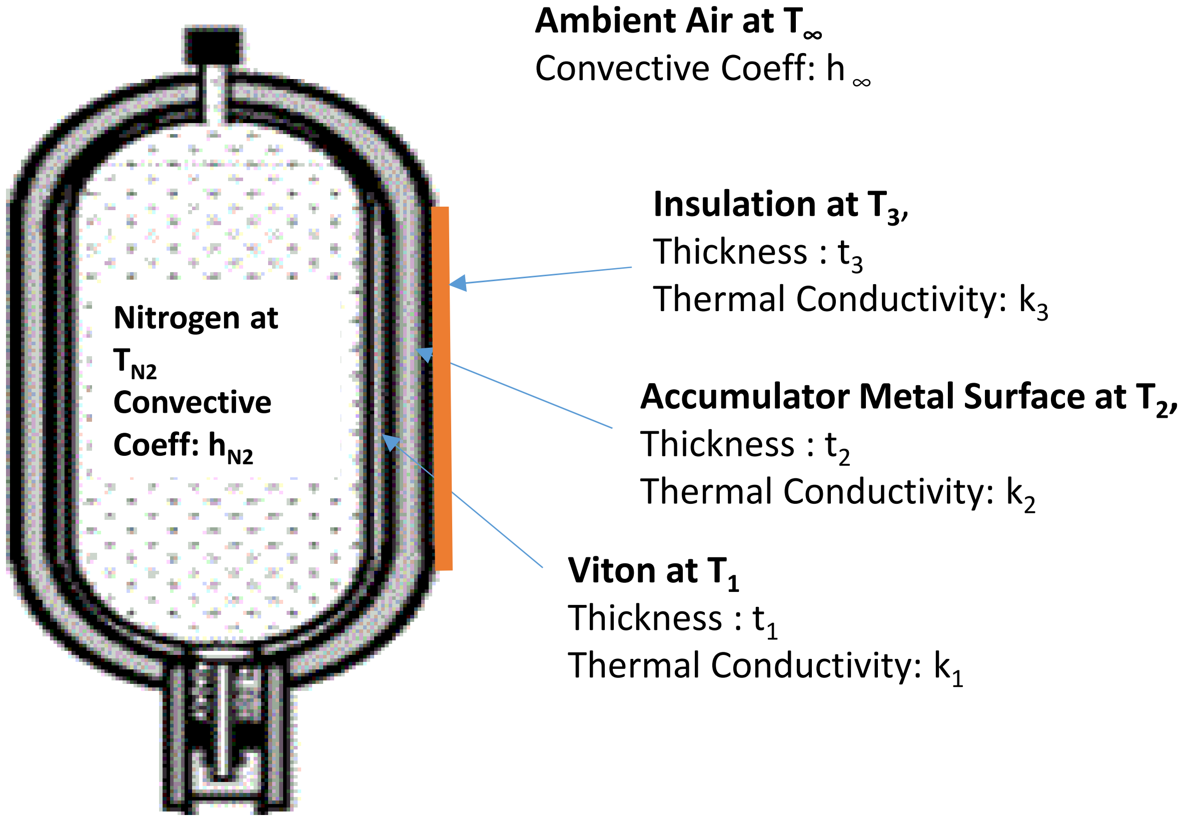
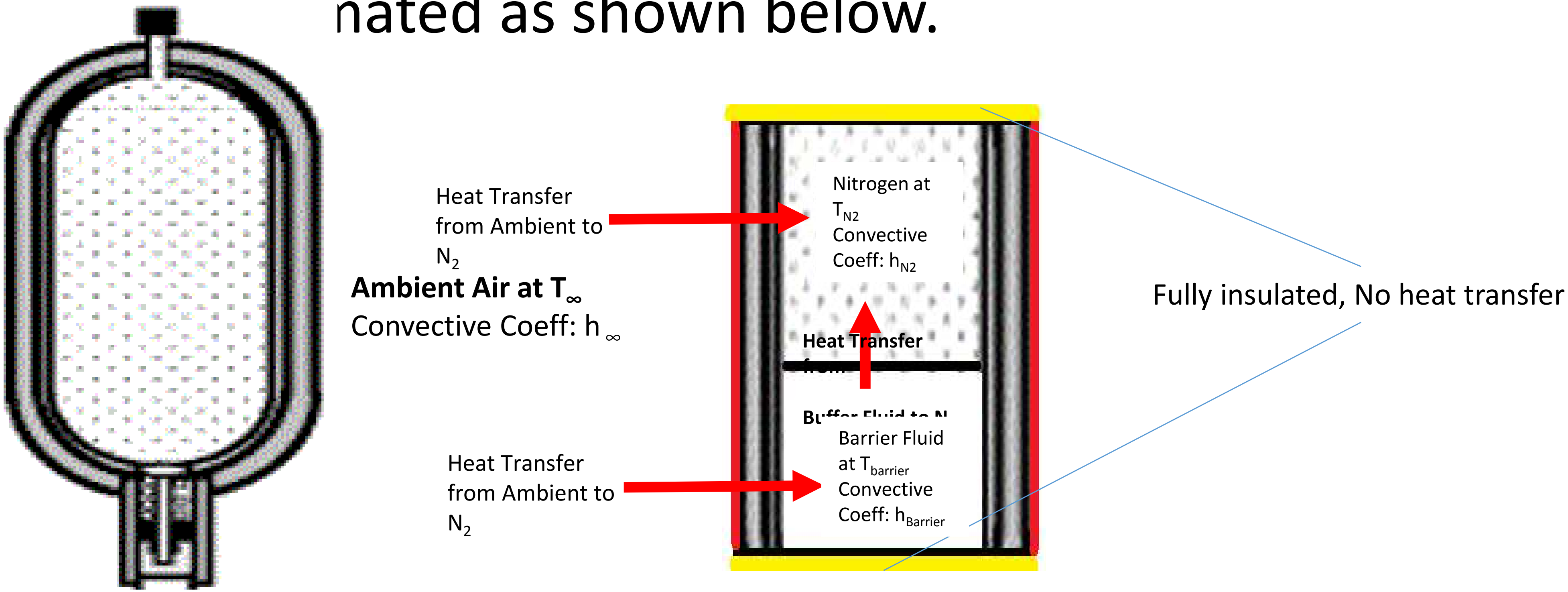
Accumulator Thermal Calculation

A typical Accumulator



Modeling

- For the calculation, the accumulator is · nated as shown below.



Assumptions

- Complex shape of a accumulator is transformed into a simple cylinder
- The top and bottom of the accumulator is completely insulated
- After refill, the bladder deflects into a simple shape for each calculation. The model is quite similar to a piston cylinder shape
- Heat transfer within the N_2 and barrier fluid is uniform.
- Convective heat transfer coefficient of stagnant air is used for inner and outer side of the accumulator
- There is not conductive heat transfer happening from the hot barrier fluid in the piping connection to the barrier fluid in the accumulator
- Ambient Temperature is changed sinusoidally

Assumptions

- For the calculation, it is assumed that the velocity of gas inside the accumulator is zero, then based on the this equation, h is assumed to be 10.45 W/m2.K

Convective Heat Transfer Coefficient for Air

The convective heat transfer coefficient for **air** flow can be approximated to

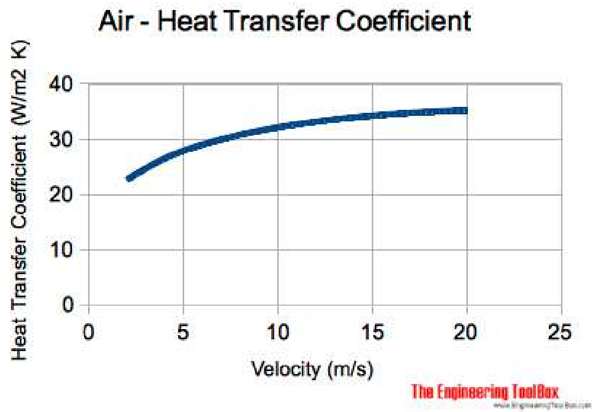
$$h_c = 10.45 - v + 10\, v^{1/2} \qquad (2)$$

where

v = relative speed between object surface and air (m/s)

Note! - this is an empirical equation and can be used for velocities *2* to *20 m/s*.

- Convective Air Flow from a single Heat Source



Steps for Modeling

- First the initial values are assumed.
- The transient heat transfer between the atmosphere and the barrier fluid is generated. When calculating this, it is assumed (not fully correct though) that there is no heat transfer to N2 as it is assumed that this effect is negligible
- Once the transient equation for the barrier heat transfer from ambient is generated, the equation for the heat transfer to N2 from ambient and barrier is formulated to understand the variation of N2 temperature

Heat transfer across Ambient to Barrier

- The methodology used is in the figure
- Only accumulator shell and insulation is taken into account
- Following sheets shows the calculation

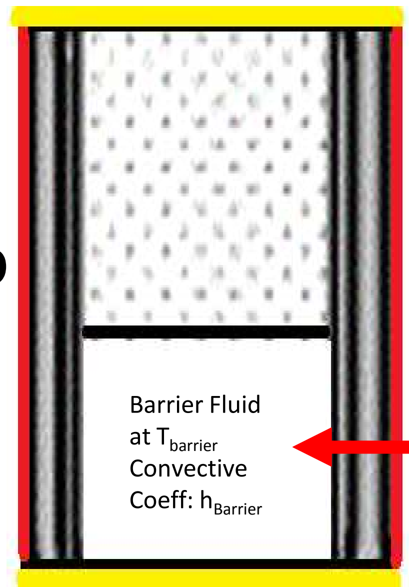
If U is defined in terms of the inside area, $A_1 = 2\pi r_1 L$, Equations 3.34 and 3.35 may be equated to yield

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{r_1}{k_A}\ln\frac{r_2}{r_1} + \frac{r_1}{k_B}\ln\frac{r_3}{r_2} + \frac{r_1}{k_C}\ln\frac{r_4}{r_3} + \frac{r_1}{r_4}\frac{1}{h_4}} \quad (3.36)$$

This definition is *arbitrary,* and the overall coefficient may also be defined in terms of A_4 or any of the intermediate areas. Note that

$$U_1A_1 = U_2A_2 = U_3A_3 = U_4A_4 = (\Sigma R_t)^{-1} \quad (3.37)$$

and the specific forms of U_2, U_3, and U_4 may be inferred from Equations 3.34 and 3.35.



Ambient Air at T_∞
Convective Coeff: h_∞

Heat Transfer
from Ambient to
N_2

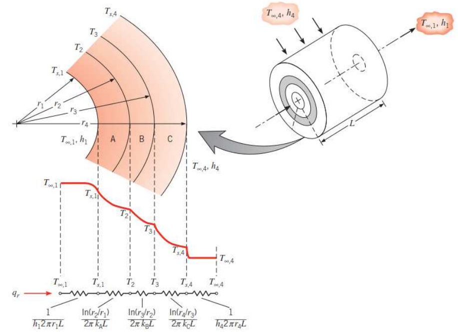


FIGURE 3.8 Temperature distribution for a composite cylindrical wall.

Heat Transfer from Ambient to Barrier fluid.

$$Q_{barrier} = \frac{T - T_{amb}}{\frac{1}{2\pi r_2 L h_2} + \frac{\ln(r_3/r_2)}{2\pi k_B L} + \frac{\ln(r_4/r_3)}{2\pi k_C L} + \frac{1}{2\pi r_4 L h_{amb}}}$$

$$Q_{barrier} = UA_{amb}(T - T_{amb})$$

$$UA_{amb}(T - T_{amb}) + mc\frac{dT}{dt} = 0.$$

$$-mc\frac{dT}{dt} = UA_{amb}\theta \qquad \theta = T - T_{amb}$$

$$d\theta = dT.$$

$$-mc\frac{d\theta}{dt} = UA_{amb}\theta.$$

$$-mc\int\frac{d\theta}{\theta} = UA_{amb}\int dt.$$

$$\ln(\theta) = -\frac{UA_{amb}}{mc}t + C$$

$$t = 0, \quad \theta_i = T_i - T_\infty.$$

$$\ln(\theta_i) = C$$

$$\ln(\theta) - \ln(\theta_i) = -\frac{UA_{amb}}{mc}t.$$

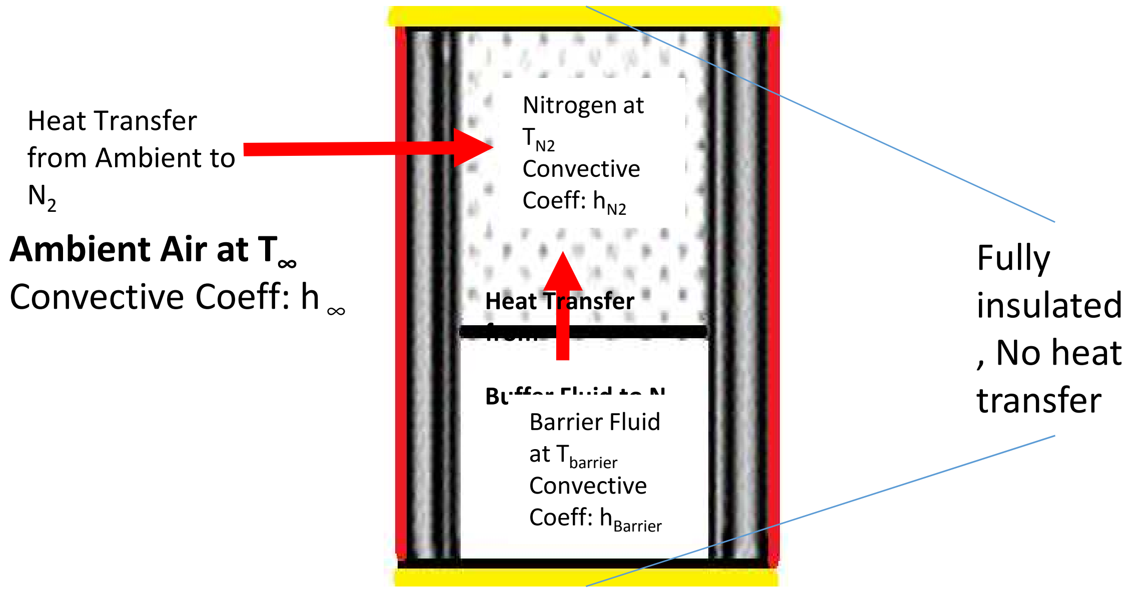
$$\ln\left(\frac{\theta}{\theta_i}\right) = -\frac{UA_{amb}t}{mc}$$

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-\left(\frac{UA_{amb}}{mc} t\right)}.$$

$$\boxed{T = T_\infty + (T_i - T_\infty)\, e^{-\left(\frac{UA_{amb}}{mc} t\right)}}$$

Heat transfer from Ambient and Barrier to N2

- Modeling is done as per figure
- Equation formulation is carried out in the next pages
- For the barrier fluid temperature, for each time step, the barrier fluid temperature calculated from previous step is used
- Ambient temperature changes sinusoidal and ambient temperature changes for each time step
- For the formulation, the transient variation of T_{amb} is not considered. Ambient T is considered as constant as it dT_{amb}/dt is very small



Heat transfer from Ambient and Barrier to N2

- Internal energy of the gas is calculated as per shown
- N2 is considered as diatomic
- http://www.webassign.net/question_assets/buelemphys1/chapter15/section15dash3.pdf
- https://www.ajdesigner.com/idealgas/ideal_gas_law_mole_equation.php#ajscroll

EXPLORATION 15.3A – A constant-volume process

A sample of monatomic ideal gas is initially at a temperature of 200 K. The gas occupies a constant volume. Heat is then added to the gas until the temperature reaches 400 K. This process is shown on the P-V diagram in Figure 15.8, where the system moves from state 1 to state 2 by the process indicated. The diagram also shows the cylinder in state 1 and again in state 2. The figure also shows the 200 K isotherm (lower) and the 400 K isotherm (higher).

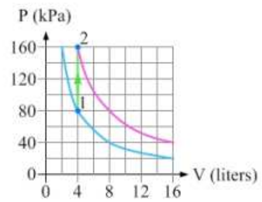


Figure 15.8: A P-V diagram showing a constant-volume process that moves a system of monatomic ideal gas from state 1 to state 2.

Step 1 – *Find the number of moles of gas in the cylinder.* Applying the ideal gas law to state 1 gives:

$$n = \frac{PV}{RT} = \frac{(80 \text{ kPa})(4.0 \text{ L})}{(8.31 \text{ J/mol K})(200 \text{ K})} = 0.19 \text{ moles}.$$

Step 2 – *Find the work done in this process.* The work done is the area under the curve for the process. Because there is no area under the curve in a constant-volume process the work done by the gas is zero: $W = 0$.

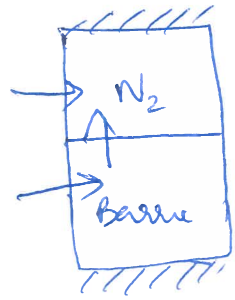
Step 3 – *Find the change in internal energy for this process.* In a constant-volume process all the heat added goes into changing the internal energy of the gas. Because the gas is monatomic we have $C_V = 3R/2$. This gives:

$$\Delta E_{int} = \frac{3}{2} n R \Delta T = \frac{3}{2}(0.19 \text{ moles})(8.31 \text{ J/mol K})(400 \text{ K} - 200 \text{ K}) = +480 \text{ J}.$$

Step 4 – *Find the heat added to the gas in this process.* The First Law of Thermodynamics tells us that $Q = \Delta E_{int} + W$, but if the work done by the gas is zero we have $Q = \Delta E_{int}$. In this case we have $Q = +480$ J.

Key ideas for a constant-volume process: There is no work done by the gas: $W = 0$.
The heat added to the gas is equal to the change in internal energy: $Q = n C_V \Delta T$.
Related End-of-Chapter Exercises: 17, 18.

Variation of N_2 Temperature



→ Impact from Ambient is considered

→ Impact from Barrier is considered.

$$\frac{5}{2} nR \frac{dT}{dt} + Q_{amb} + Q_{Barrier} = 0.$$

$$Q_{amb} = \frac{T - T_{amb}}{\frac{1}{2\pi r_1 L h_1} + \frac{\ln(r_2/r_1)}{2\pi k_A L} + \frac{\ln(r_3/r_2)}{2\pi k_B L} + \frac{\ln(r_4/r_3)}{2\pi k_C L} + \frac{1}{2\pi r_4 L h_4}}.$$

$$= UA'_{amb} (T - T_{amb})$$

$$Q_{Barrier} = \frac{T - T_{Barrier}}{\left(\frac{L_A}{K_A A}\right)}$$

$$= UA'_{Barrier} (T - T_{Barrier})$$

$$UA'_{amb}(T - T_{amb}) + UA'_{Barrier}(T - T_{Barrier}) + \frac{5}{2} nR \frac{dT}{dt} = 0$$

$$\frac{5}{2} nR \left(\frac{\Delta T}{dt}\right) = -\left[UA'_{amb}(T - T_{amb}) + UA'_{Barrier}(T - T_{Barrier})\right]$$

$$\frac{5}{2} nR \left(\frac{\Delta T}{dt}\right) = -T\left(UA'_{amb} + UA'_{Barrier}\right) + \left(UA'_{amb} T_{amb} + UA'_{Barrier} T_{Barrier}\right)$$

$$\alpha = -\left(UA'_{Barrier} + UA'_{amb} \right)$$

$$\beta = UA'_{amb} T_{amb} + UA'_{Barrier} T_{Barrier}.$$

$$\gamma = \frac{5}{2} nR.$$

$$\gamma \frac{dT}{dt} = \alpha T + \beta.$$

$$\frac{dT}{dt} = \left(\frac{\alpha}{\gamma}\right) T + \frac{\beta}{\gamma}.$$

to make it simple ;

$$+\frac{\alpha}{\gamma} = -A \quad , \quad \frac{\beta}{\gamma} = B$$

$$\frac{dT}{dt} = -AT + B.$$

$$\frac{dT}{dt} + AT = B.$$

multiply by $\mu(t) = e^{\int A dt} = e^{At}.$

$$e^{At} \frac{dT}{dt} + e^{At} AT = e^{At} B.$$

$$\int (e^{At} \cdot T)' \, d\cancel{T} = \int e^{At} B \, dt$$

$$e^{At} T + K = \frac{B}{A} e^{At} + C$$

$$e^{At}T = \frac{B}{A}e^{At} + (C-k) \qquad C-k = D$$

$$e^{At}T = \frac{B}{A}e^{At} + D$$

at $t=0$, $T = T_{N_2}$ = initially temp of N_2.

$$\therefore \; T = \frac{B}{A} + De^{-At}.$$

@ $t=0$

$$T_{N_2} = \frac{B}{A} + D$$

$$\boxed{D = T_{N_2} - \frac{B}{A}}$$

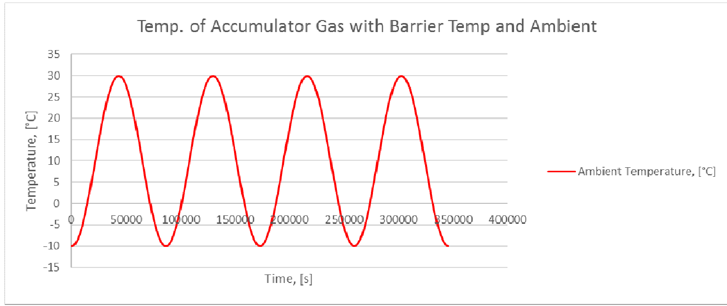
$$\boxed{T = \frac{B}{A} + \left(T_{N_2} - \frac{B}{A}\right)e^{-At}}$$

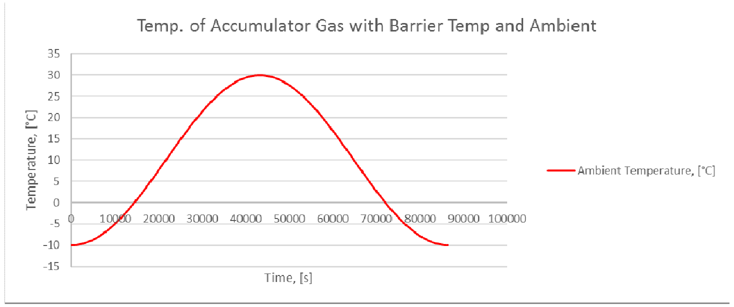
$$A = \frac{-\alpha}{V} = \frac{UA'_{Barrier} + UA'_{amb}}{\frac{5}{2}nR}$$

$$B = \frac{UA'_{amb}T_{amb} + UA'_{Barrier}T_{Barrier}}{\frac{5}{2}nR}.$$

Ambient Temperature Variation

- Sinusoidal variation assumed
- Assumed that Variation of ambient temperature is not from change in barrier or N2
- Shown is a temperature variation between -10 to 30°C in a day (24 hrs = 86400 seconds





Calculation Steps

- First try to estimate the critical insulation thickness and outer insulation temperature based on initial N2 gas temperature and ambient temperature

- Ref pg: 1

If U is defined in terms of the inside area, $A_1 = 2\pi r_1 L$, Equations 3.34 and 3.35 may be equated to yield

$$U_1 = \frac{1}{\dfrac{1}{h_1} + \dfrac{r_1}{k_A}\ln\dfrac{r_2}{r_1} + \dfrac{r_1}{k_B}\ln\dfrac{r_3}{r_2} + \dfrac{r_1}{k_C}\ln\dfrac{r_4}{r_3} + \dfrac{r_1}{r_4}\dfrac{1}{h_4}} \tag{3.36}$$

This definition is *arbitrary*, and the overall coefficient may also be defined in terms of A_4 or any of the intermediate areas. Note that

$$U_1A_1 = U_2A_2 = U_3A_3 = U_4A_4 = (\Sigma R_t)^{-1} \tag{3.37}$$

and the specific forms of U_2, U_3, and U_4 may be inferred from Equations 3.34 and 3.35.

Variation of Ambient Temperature on Accumulator

Temperature and Precharge Details

Ambient Temperature, [T_{∞}]	-10	°C	263.2	°K
Filling Barrier Temperature, [$T_{Barrier}$]	35	°C	308.2	°K
N2 Filling Temperature, [T_i]	10	°C	283.2	°K
N2 Refill Pressure	10.0	barg	10.0	barg
N2 Bladder Volume	0.027	m3		
Barrier Fluid Volume	35.0	L	0.035	m^3
Barrier Fluid Density	800.0	kg/m^3		
Univeral Gas Constant	8.31	J/mol °K		

Dimensional Details

Inner Diameter of the Accumulator Bladder, [R]	212	mm	0.212	m
Total Height of the Accumulator, [L]	1	m	1.000	m
Height of the Bladder, [$L_{Bladder}$]	0.76	m	0.763	m
Height of the Barrier Fluid, [$L_{Barrier}$]	0.24	m	0.237	m
Thickness of the Bladder, [$t_{bladder}$]	5	mm	0.005	m
Thickness of the shell, [t_{shell}]	7	mm	0.007	m
Thickness of the Insulation, [$t_{Insulation}$]	1	mm	0.001	m
Critical Thickness	0.0025	m		

r1	0.106	m
r2	0.111	m
r3	0.118	m
r4	0.119	m

Thermal Details

Convective Heat Transfer Coefficicent of N2, [h_{N2}]	10	$W/m^2\,°K$		
Convective Heat Transfer Coefficicent of Barrier Fluid, [$h_{Barrier}$]	100	$W/m^2\,°K$		
Specific Heat of Barrier Fluid, [$C_{Barrier}$]	2500	J/kg°C		
Thermal Conductivity of Bladder, [$k_{bladder}$]	0.5	W/m°K	Bladder Material	Viton
Thermal Conductivity of Accumulator Shell, [k_{shell}]	14.01	W/m°K	Accumulator Material	Alloy C-276
Thermal Conductivity of Insulation, [$k_{insulation}$]	0.025	W/m°K	Insulating Material	Polyisocynurate
Convective Heat Transfer Coefficicent of Ambient Air, [h_{air}]	10	$W/m^2\,°K$		

$UA_{ambient}$	2.16	W/°K
$UA_{Barrier}$ to the N2 Fluid	3.53	W/°K
$UA_{Ambient}$ to the Buffer Fluid	1.17	W/°K
Number of Moles of Gas in the Bladder, [n]	11.45	moles
Exponential Constant, [2UA/(5nR)]	0.0091	
A = ($UA_{barrier}$ + $UA_{ambient}$)/[5nR/2]	0.024	
B = ($T_{ambient}$*$UA_{barrier}$ + $T_{barrier}$*$UA_{ambient}$)/[5nR/2]	6.705	

Enter the Sinusoidal Variation

Total Duration of the Variation	1	day		
	86400	Seconds		
Maximum Temperature during the day	30	°C	303.2	°K
Minimum Temperature during the day	-10	°C	263.2	°K
Total Duration to Plot	1	day		
	86400	Seconds		

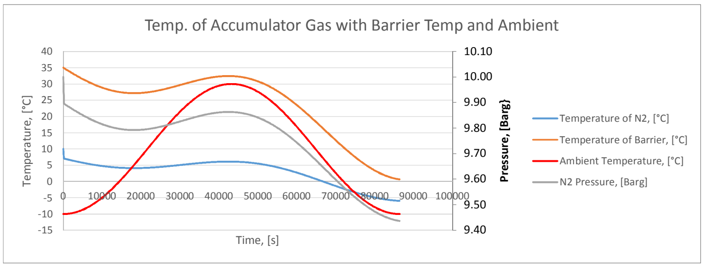
Time	**24**	**Hours**	**86400**	**seconds**

Heat from Barrier Not Considered

Temperature after 24 Hours	263	°K	-9.9	°C

Heat from Barrier Considered

Time	24	Hours	86400	seconds
Temperature of Barrier Fluid	274	°K	0.8	°C
A = ($UA_{barrier}$ + $UA_{ambient}$)/[5nR/2]	0.024			
B = ($T_{ambient}$*$UA_{barrier}$ + $T_{barrier}$*$UA_{ambient}$)/[5nR/2]	6.393			
Temperature after 24 Hours	267	°K	-5.8	°C



Variation of Ambient Temperature on Accumulator

Temperature and Precharge Details

Ambient Temperature, $[T_{\infty}]$	-10	°C	263.2	°K
Filling Barrier Temperature, $[T_{Barrier}]$	35	°C	308.2	°K
N2 Filling Temperature, $[T_i]$	10	°C	283.2	°K
N2 Refill Pressure	10.0	barg	10.0	barg
N2 Bladder Volume	0.027	m3		
Barrier Fluid Volume	35.0	L	0.035	m^3
Barrier Fluid Density	800.0	kg/m^3		
Univeral Gas Constant	8.31	J/mol °K		

Dimensional Details

Inner Diameter of the Accumulator Bladder, [R]	212	mm	0.212	m			
Total Height of the Accumulator, [L]	1	m	1.000	m			
Height of the Bladder, $[L_{Bladder}]$	0.76	m	0.763	m			
Height of the Barrier Fluid, $[L_{Barrier}]$	0.24	m	0.237	m	r1	0.106	m
Thickness of the Bladder, $[t_{bladder}]$	5	mm	0.005	m	r2	0.111	m
Thickness of the shell, $[t_{shell}]$	7	mm	0.007	m	r3	0.118	m
Thickness of the Insulation, $[t_{Insulation}]$	1	mm	0.001	m	r4	0.119	m
Critical Thickness	0.0025	m					

Thermal Details

Convective Heat Transfer Coefficient of N2, $[h_{N2}]$	10	W/m^2 °K		
Convective Heat Transfer Coefficient of Barrier Fluid, $[h_{Barrier}]$	100	W/m^2 °K		
Specific Heat of Barrier Fluid, $[C_{Barrier}]$	2500	J/kg°C		
Thermal Conductivity of Bladder, $[k_{bladder}]$	0.5	W/m°K	Bladder Material	Viton
Thermal Conductivity of Accumulator Shell, $[k_{shell}]$	14.01	W/m°K	Accumulator Material	Alloy C-276
Thermal Conductivity of Insulation, $[k_{insulation}]$	0.025	W/m°K	Insulating Material	Polyisocynurate
Convective Heat Transfer Coefficient of Ambient Air, $[h_{air}]$	10	W/m^2 °K		

$UA_{ambient}$	2.16	W/°K
$UA_{Barrier}$ to the N2 Fluid	3.53	W/°K
$UA_{Ambient}$ to the Buffer Fluid	1.17	W/°K
Number of Moles of Gas in the Bladder, [n]	11.45	moles
Exponential Constant, [2UA/(5nR)]	0.0091	
$A = (UA_{barrier} + UA_{ambient})/[5nR/2]$	0.024	
$B = (T_{ambient}{*}UA_{barrier} + T_{barrier}{*}UA_{ambient})/[5nR/2]$	6.705	

Enter the Sinusoidal Variation

Total Duration of the Variation	1	day		
	86400	Seconds		
Maximum Temperature during the day	15	°C	288.2	°K
Minimum Temperature during the day	-10	°C	263.2	°K
Total Duration to Plot	2	day		
	172800	Seconds		

Time	**24**	**Hours**	**86400**	**seconds**

Heat from Barrier Not Considered

Temperature after 24 Hours	263	°K	-9.9	°C

Heat from Barrier Considered

Time	24	Hours	86400	seconds
Temperature of Barrier Fluid	274	°K	0.8	°C
$A = (UA_{barrier} + UA_{ambient})/[5nR/2]$	0.024			
$B = (T_{ambient}{*}UA_{barrier} + T_{barrier}{*}UA_{ambient})/[5nR/2]$	6.393			
Temperature after 24 Hours	267	°K	-5.8	°C