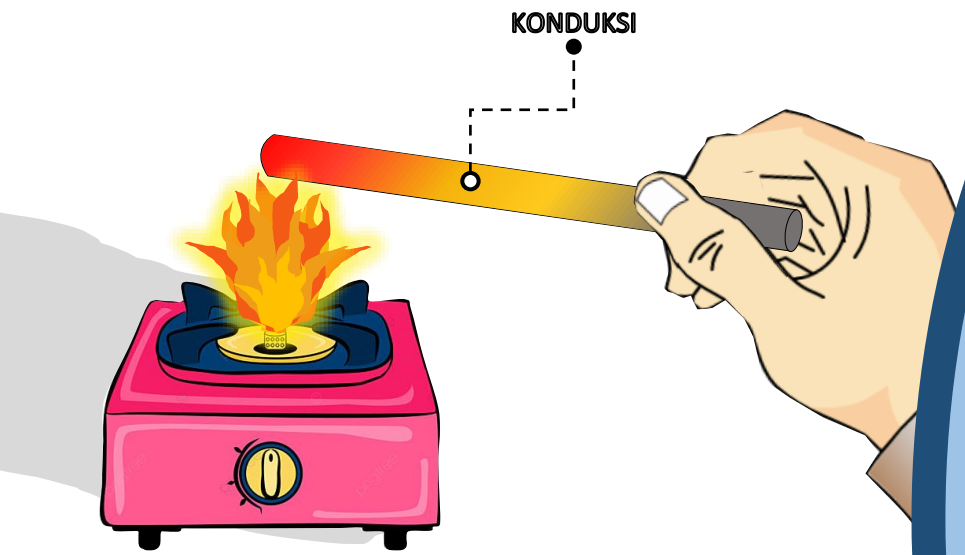
2. PERPINDAHAN PANAS KONDUKSI



FAKULTAS TEKNIK
Universitas Pattimura

DAFTAR POKOK BAHASAN

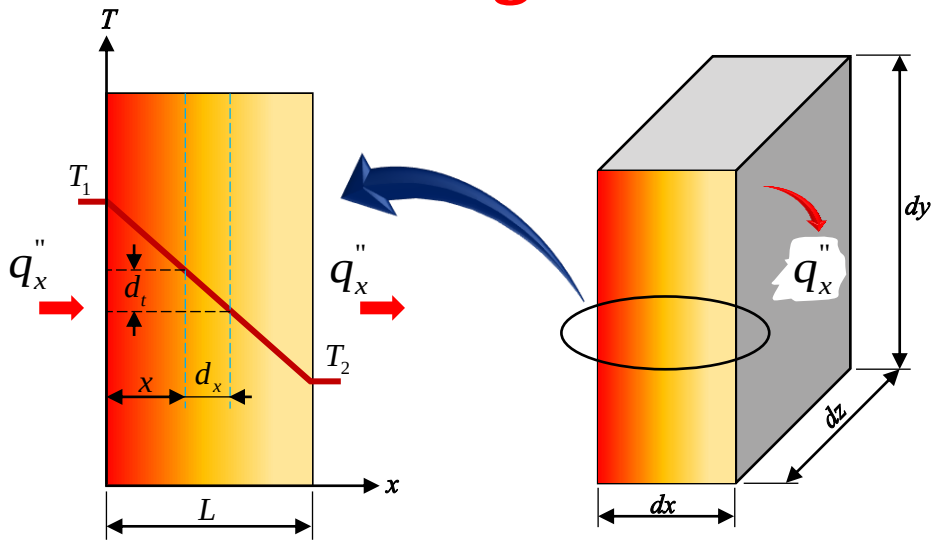
1. Konduksi panas satu dimensi melalui dinding datar dan dinding komposit.
2. Konduksi panas satu dimensi melalui pipa hollow dan pipa hollow komposit.
3. Konduksi panas satu dimensi melalui bejana berbentuk bola hollow dan bola komposit.

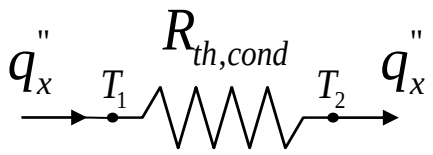
SPEAKER

1

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Dinding datar





Persamaan umum konduksi panas:

$$\frac{\partial^2 T}{dx^2}+\frac{\partial^2 T}{dy^2}+\frac{\partial^2 T}{dz^2}+\frac{q_g}{k}=\frac{1}{\alpha}\cdot\frac{\partial T}{\partial \tau}$$

L = ketebalan dinding

A = luas penampang melintamg didinding.

k = konduktivitas termal dinding material.

T_1, T_2 = temperatur masing-masing permukaan dinding.

SPEAKER

1 Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Panas melalui dinding datar dapat dihitung dengan menggunakan Hukum Fourier:

$$q''_x = -k\frac{dT}{dx} \quad dengan \quad \frac{dT}{dx} = \frac{T_2 - T_1}{L}$$

(Dimana, dT/dx = Temperature gradient**)**

$$q''_x = -k\frac{T_2 - T_1}{L} \quad atau \quad q''_x = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L} \quad atau \quad q''_x = k\frac{T_1 - T_2}{(L/kA)} = k\frac{(T_1 - T_2)}{(R_{th})_{kond}}$$

dimana :

$(R_{th})_{kond}$ = Tahanan termal untuk konduksi panas dimana equivalen dengan tahanan listrik pada gambar b.

- $(R_{th})_{kond} = L / kA$
- Berat dinding, $W = \rho\, A\, L$
- Maka:

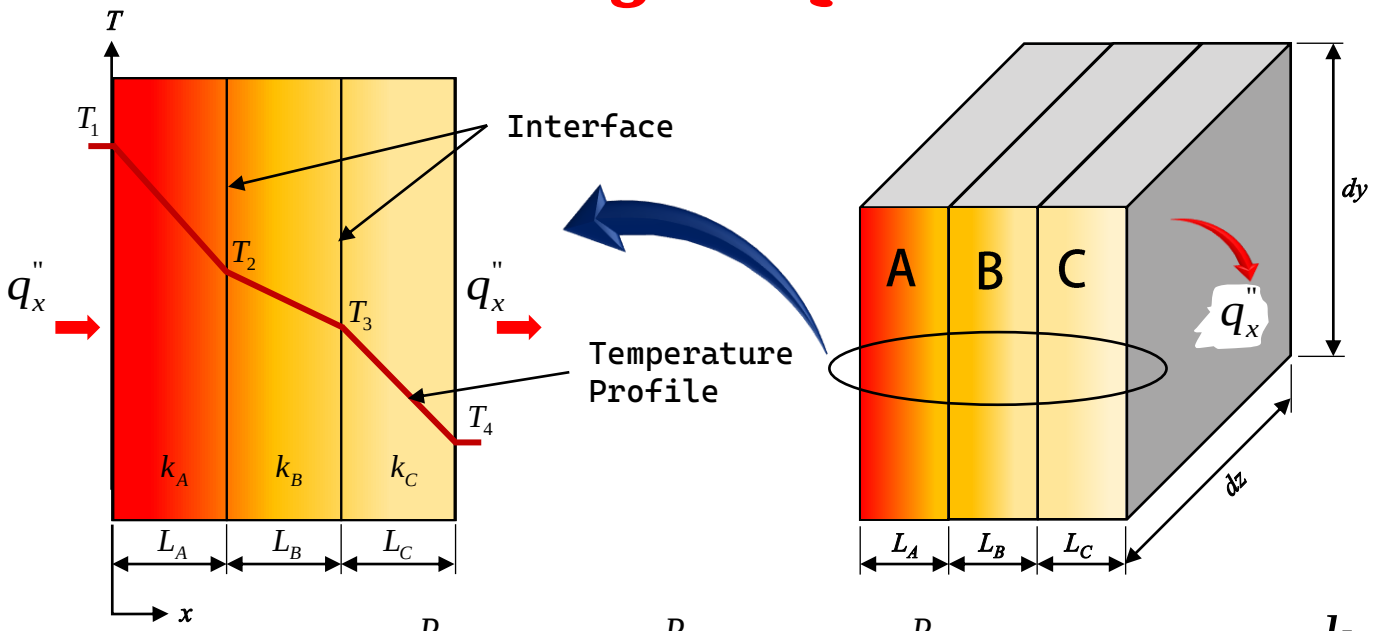
$$W = \rho\, A.\,(R_{th})_{cond.}\, kA = (\rho.k)A^2.(R_{th})_{cond.}$$

SPEAKER

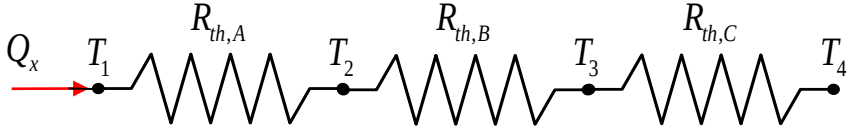
1

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Dinding komposit



- L_A, L_B, L_C = tebal slab atau lapisan A, B, C
- k_A, k_B, k_C = konduktivitas termal A, B, C
- t_1, t_4 ($t_1 > t_4$) = temperatur permukaan dinding 1 dan 4
- t_2, t_3 = temperatur pada interface 2 dan 3

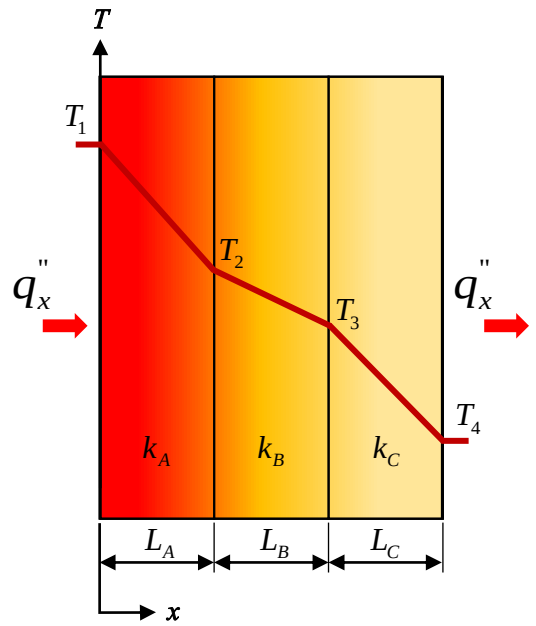


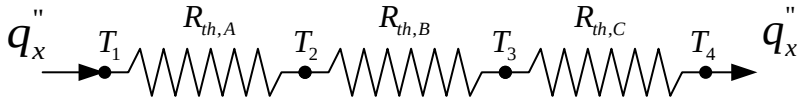
$$Q_x = \frac{k_A \cdot A(T_1 - T_2)}{L_A} = \frac{k_B \cdot A(T_2 - T_3)}{L_B} = \frac{k_C \cdot A(T_3 - T_4)}{L_C}$$

$$R_{th,A} = \frac{k_A \cdot A(T_1 - T_2)}{L_A} \qquad R_{th,B} = \frac{k_B \cdot A(T_2 - T_3)}{L_B} \qquad R_{th,C} = \frac{k_C \cdot A(T_3 - T_4)}{L_C}$$

1 Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

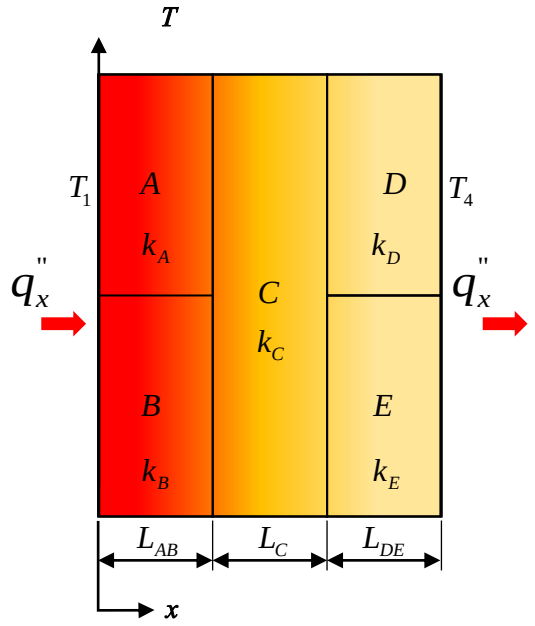
Dinding komposit susunan seri



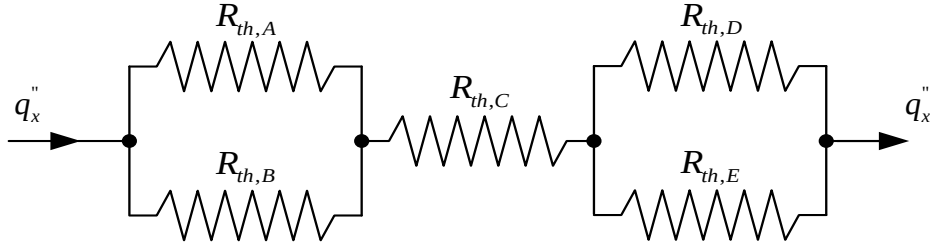


$$q_x'' = \frac{k_A \cdot A(T_1 - T_2)}{L_A} = \frac{k_B \cdot A(T_2 - T_3)}{L_B} = \frac{k_C \cdot A(T_3 - T_4)}{L_C}$$

Dinding komposit susunan paralel



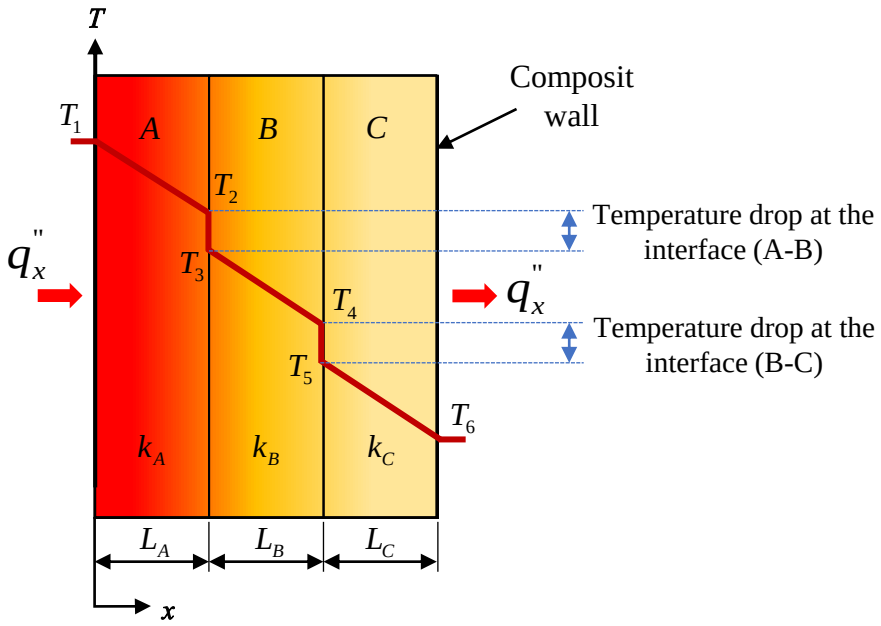
- $\frac{1}{R_{th,eq}} = \frac{L_A}{k_A \cdot A_A} + \frac{L_B}{k_B \cdot A_B}$
- $\frac{1}{R_{th,C}} = \frac{L_C}{k_C \cdot A_C}$
- $\frac{1}{R_{th,eq}} = \frac{L_D}{k_D \cdot A_D} + \frac{L_E}{k_E \cdot A_E}$
- $R_{tot} = R_{th,eq} + R_{th,C} + R_{th,eq}$
- $q_x'' = \frac{\Delta T}{R_{tot}}$



SPEAKER

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Tahanan termal kontak



$$R_{(th-AB)\,\text{cont}} \cdot = \frac{(T_2 - T_3)}{q''_x / A}$$

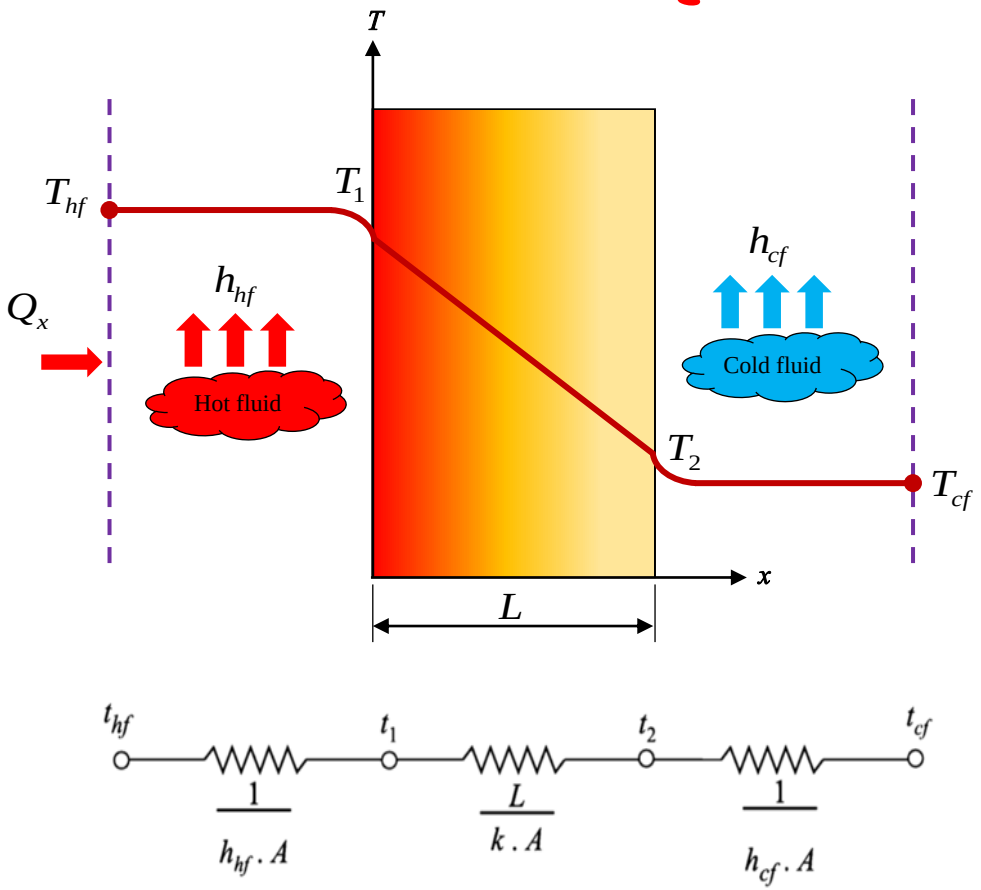
$$R_{(th-BC)\,\text{cont}} \cdot = \frac{(T_4 - T_5)}{q''_x / A}$$

1

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Perpindahan kalor keseluruhan

$$U = \frac{1}{\frac{1}{h} + \frac{L}{k} + \frac{1}{h_{cf}}}$$



Dimana:

L = tebal dinding logam.

k = konduktivitas termal material dinding

t_1 = temperatur permukaan 1

t_2 = temperatur permukaan 2

t_{hf} = temperatur fluida panas (hot fluid)

t_{cf} = temperatur fluida dingin (cold fluid)

h_{hf} = koefisien perpindahan panas dari fluida panas ke dinding logam

h_{cf} = koefisien perpindahan panas dari dinding logam ke fluida dingin

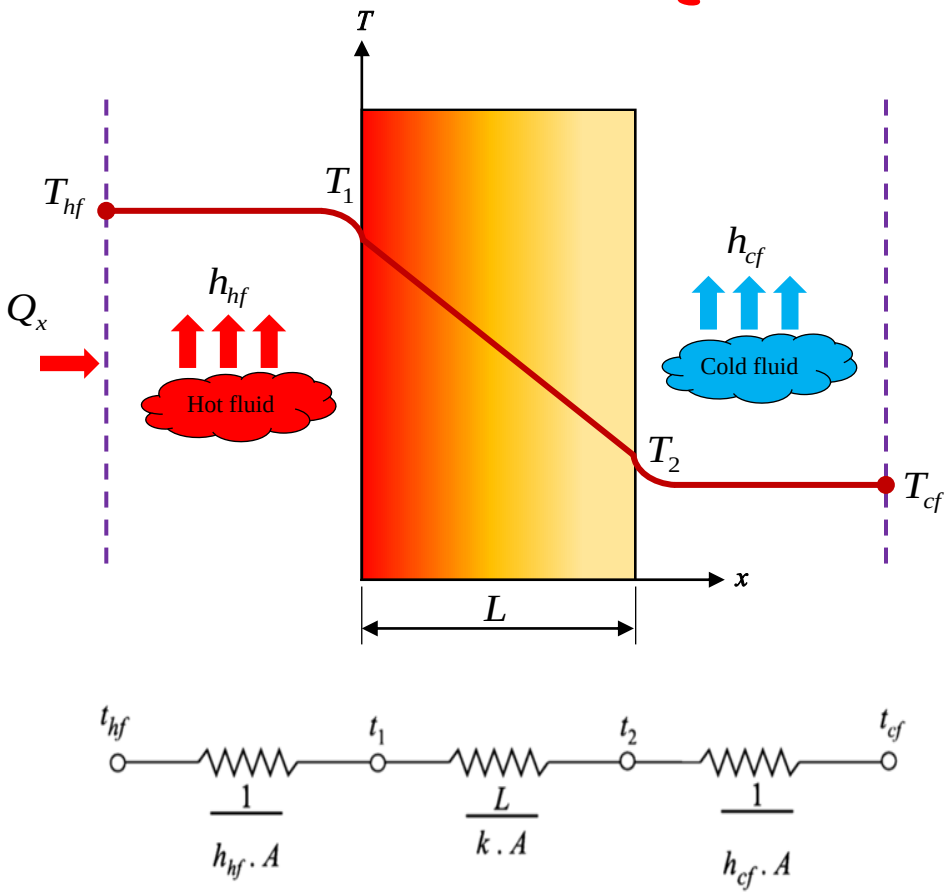
$$Q = h_{hf} A\left(T_{hf} - T_1\right) \qquad Q = \frac{k \cdot A\left(T_1 - T_2\right)}{L} \qquad Q = h_{cf} A\left(T_2 - T_{cf}\right)$$

SPEAKER

1

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Perpindahan kalor keseluruhan



$$\left(T_{hf} - T_1\right) = \frac{Q}{h_{hf} \cdot A}$$

$$\left(T_1 - T_2\right) = \frac{Q \cdot L}{k \cdot A}$$

$$\left(T_2 - T_{cf}\right) = \frac{Q}{k_{cf} \cdot A}$$

$$T_{hf} - T_{cf} = Q\left[\frac{1}{h_{hf} \cdot A} + \frac{L}{k \cdot A} + \frac{1}{h_{cf} \cdot A}\right]$$

$$Q = \frac{A\left(T_{hf} - T_{cf}\right)}{\left(\frac{1}{h_{hf}}\right) + \left(\frac{L}{k}\right) + \left(\frac{1}{h_{cf}}\right)}$$

$$Q = U \cdot A\left(T_{hf} - T_{cf}\right) = \frac{A\left(T_{hf} - T_{cf}\right)}{\left(\frac{1}{h_{hf}}\right) + \left(\frac{L}{k}\right) + \left(\frac{1}{h_{cf}}\right)}$$

$$U = \frac{1}{\left(\frac{1}{h_{hf}}\right) + \left(\frac{L}{k}\right) + \left(\frac{1}{h_{cf}}\right)}$$

SPEAKER

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Konduksi panas satu dimensi

Contoh 1.1

Tebal slab *L = 0,25 m*. Temperatur salah satu permukaan 100 ^oC dan permukaan yang lain 0 ^oC. Hitunglah *net flux* melalui slab yang terbuat dari tembaga murni dimana konduktivitas termal 387,6 W/m ^oC.

Penyelesaian,

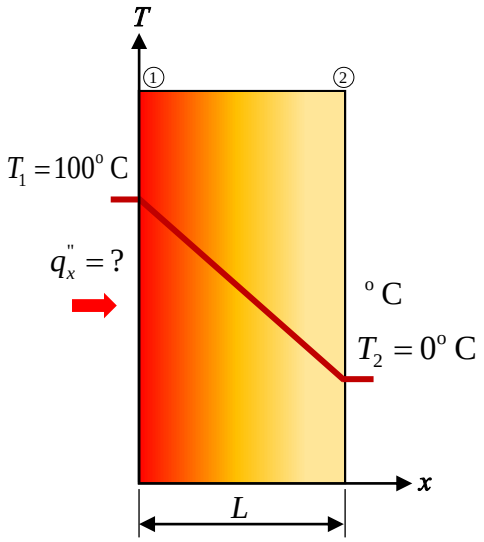
- **Dik:**

L = 0,25 m; t_1 = 100 ^oC, t_2 = 0 ^oC; k = 387,6 W/m ^oC.

- **Asumsi:**

  - stady state

- **Ske:**



- **Pers. dasar:**

$$q_x'' = -k\frac{dT}{dx} \qquad q_x'' = -k\frac{T_2 - T_1}{L}$$

- **Hasil**

$$q_x'' = -387.6\,\text{W/ m.}^o\text{C} \times \frac{0^o\text{C} - 100^o\text{C}}{0.25\,\text{m}}$$

$$= 1.55 \times 10^5\ \text{W/ m}^2$$

Konduksi panas satu dimensi melalui dinding datar dan dinding komposit

Konduksi panas dinding kompost

Contoh 1.2

Suatu dinding reaktor, tebal 320 mm dimana terdiri dari lapisan bagian dalam batu bata tahan api / *fire brick* (k = 0,84 W/m^{o}C) dan insulasi (k = 0,16 W/m^{o}C). Reaktor beroperasi pada temperatur 1325 ^{o}C dan temperatur lingkungan 25 ^{o}C.

(i) Hitunglah tebal *fire brick* dan insulasi yang mana memberikan kerugian panas minimum.

(ii) Hitunglah kerugian panas dengan asumsi awal bahwa material insulasi mempunyai temperatur maksimum 1200 ^{o}C.

Penyelesaian,

Dik:

$t_1 = 1325°C;\ t_2 = 1200°C,\ t_3 = 25°C$

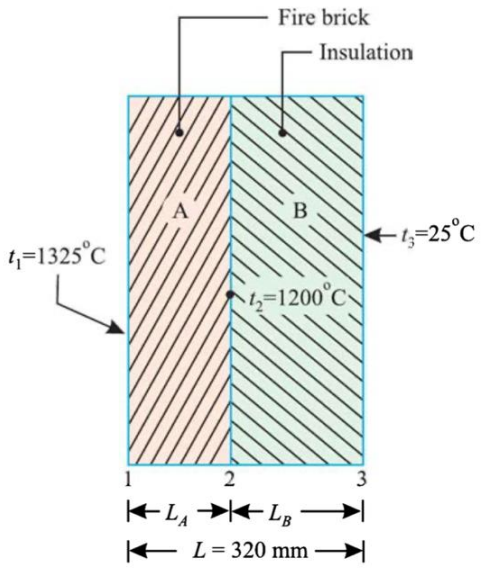
$L_A + L_B = L = 320$ mm or 0.32 m

$L_B = (0.32 - L_A)$;

$k_A = 0.84$ W/m°C;

$k_B = 0.16$ W/m°C.

Skema:



Pers. dasar:

$$q = \frac{t_1 - t_3}{L_A/k_A + L_B/k_B} = \frac{t_1 - t_2}{L_A/k_A} = \frac{t_2 - t_3}{L_B/k_B}$$

Hasil:

$$\frac{(1325 - 25)}{L_A/0.84 + L_B/0.16} = \frac{(1325 - 1200)}{L_A/0.84}$$

$$\frac{1300}{1.190\,L_A + 6.25\,(0.32 - L_A)} = \frac{105}{L_A}$$

$$\frac{1300}{1.190\,L_A + 2 - 6.25\,L_A} = \frac{105}{L_A}$$

$$\frac{1300}{2 - 5.06\,L_A} = \frac{105}{L_A}$$

$$1300\,L_A = 105\,(2 - 5.06\,L_A)$$

$$1300\,L_A = 210 - 531.3\,L_A$$

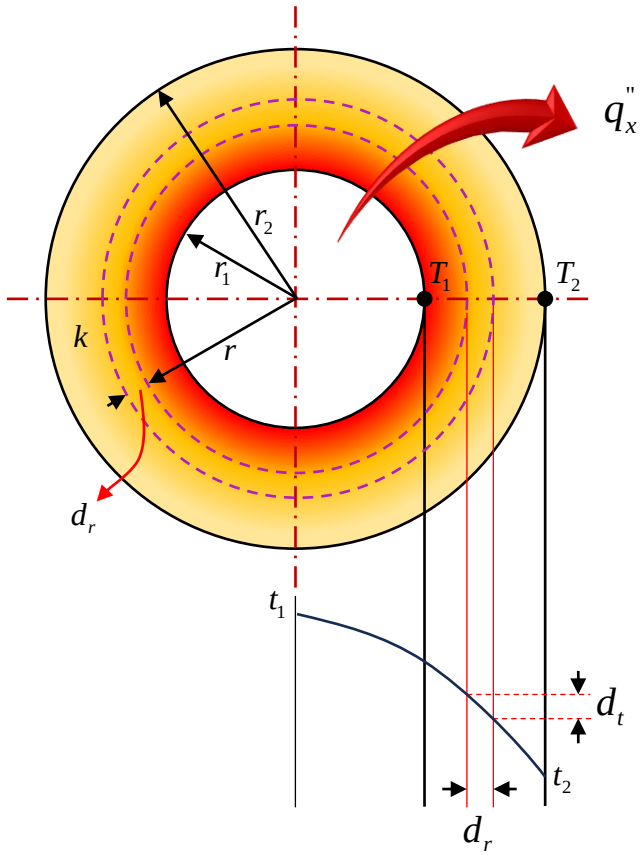
$$L_A = \frac{210}{(1300 + 531.3)} = 0.1146 \text{ m or } \mathbf{114.6\ mm}$$

$L_B = 320 - 114.6 = \mathbf{205.4\ mm}$

$$q = \frac{t_1 - t_2}{L_A/k_A} = \frac{1325 - 1200}{0.1146/0.84} = \mathbf{916.23\ W/m^2}$$

2 Konduksi panas satu dimensi melalui pipa hollow dan pipa hollow komposit

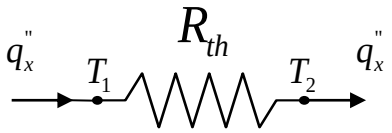
Pipa hollow



$$q_x^{"} = -kA \cdot \left(\frac{dT}{dr} \right)$$

$$= -k \cdot 2\pi r \cdot L \frac{dT}{dr} \quad \textit{Per unit time}$$

$$R_{th} = \frac{\ln (r_2 / r_1)}{2\pi k L})$$



$$q_x^{"} = \frac{k \cdot 2\pi L(T_1 - T_2)}{\ln(r_2 - r_1)} = \frac{(T_1 - T_2)}{\left[\frac{\ln(r_2 - r_1)}{2k\pi L} \right]}$$

Dimana,

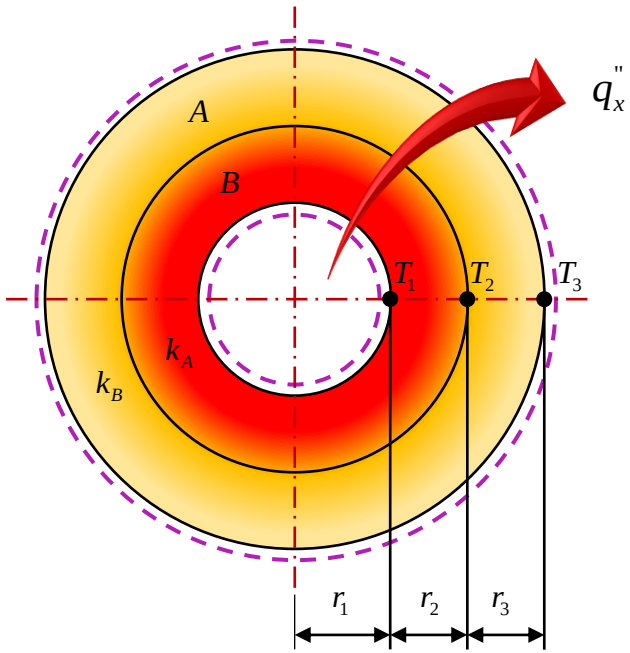
r_1, r_2 = radius dalam dan luar

T_1, T_2 = temperatur permukaan dalam dan luar.

k = koefisien konduktivitas termal

2 Konduksi panas satu dimensi melalui pipa hollow dan pipa hollow komposit

Pipa hollow komposit



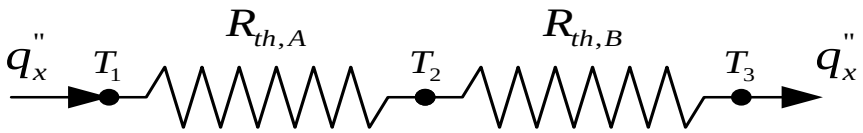
T_{hf} =temperatur fluida panas yang mengalir di dalam pipa.
T_{cf} = temperatur fluida dingin (temperature atmosfir)
k_A = konduktivitas termal lapisan dalam A.
k_B = konduktivitas termal lapisan luar B.
T_1, t_2, t_3 = temperatur titik 1, 2 dan 3
L = panjang pipa komposit
h_{hf}, h_{cf} = koefisien perpindahan panas di dalam dan di luar pipa

$$T_{hf} - T_1 = \frac{q_x''}{h_{hf} \cdot r_1 \cdot 2\pi L}$$

$$T_1 - T_2 = \frac{q_x''}{\frac{kA \cdot 2\pi L}{\ln(r_2/r_1)}}$$

$$T_2 - T_3 = \frac{q_x''}{\frac{kA \cdot 2\pi L}{\ln(r_3/r_2)}}$$

$$T_3 - T_{hf} = \frac{q_x''}{h_{hf} \cdot r_3 \cdot 2\pi L}$$



$$q_x'' = \frac{k_A \cdot 2\pi L(T_1 - T_3)}{\ln(r_2/r_1)} = \frac{k_B \cdot 2\pi L(T_1 - T_3)}{\ln(r_2/r_1)} = h_{cf} \cdot 2\pi r^3 \cdot L(T_3 - T_{cf})$$

2

Konduksi panas satu dimensi melalui pipa hollow dan pipa hollow komposit

Pipa hollow

Contoh 1.1

Diameter dalam suatu pipa gas 2 mm dan Panjang 25 cm. Gas dipanaskan dengan kawat listrik berdiameter 50 mikron (0,05 mm) yang ditempatkan sepanjang sumbu pipa. Arus listrik 0,5 Ampere dan voltage drop sepanjang elemen pemanas 4 Volt. Jika temperatur kawat 175 ^oC dan temperatur dinding pipa bagian dalam 150 ^oC, hitunglah konduktivitas termal pipa gas.

Penyelesaian:

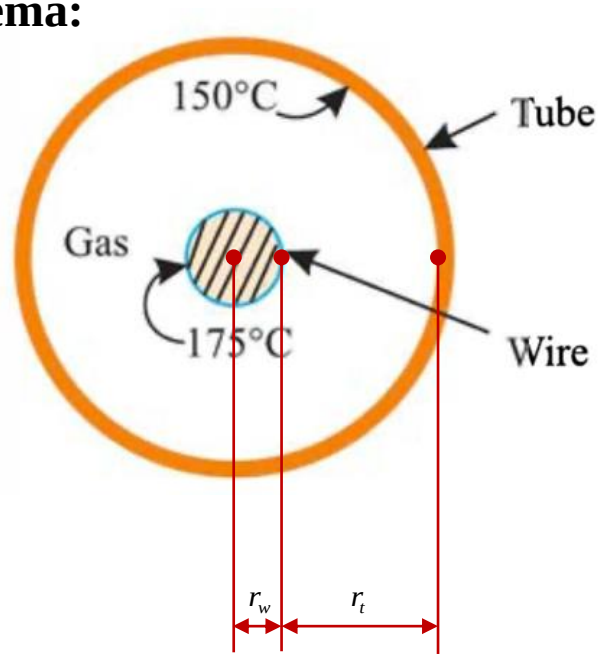
Dik:

Radius dalam pipa, r_t = 2 mm
Panjang pipa, L = 25 cm = 0.25 m
Diameter kawat listrik, r_w = 0.025 mm
Suhu permukaan dalam pipa, T_t = 150° C
Suhu permukaan kawat listrik T_w = 175°C
Arus listrik, I = 0.5 A
Tegangan listrik, V = 4 Volt

Ditanya:

$k = \ldots\ldots\ldots ?$

Skema:



Pers. dasar:

$$q_x'' = \frac{k \cdot 2\pi L(T_1 - T_2)}{\ln(r_2 - r_1)}$$

Hasil:

$$q_x'' = \frac{2\pi k \times 0.25(175 - 150)}{\ln(1/0.025)} = 10.645 \text{ kW} \quad \ldots(i)$$

Also, $q_x'' = VI = 4 \times 0.5 = 2.0$ W $\quad \ldots(ii)$

From (i) and (ii), we get

$10.645\,k = 2.0$

or, $k = \mathbf{0.188\ W/m°C.}$ **(Ans.)**

SPEAKER

Konduksi panas satu dimensi melalui pipa hollow dan pipa hollow komposit

Pipa hollow komposit

Contoh 1.2

Suatu pipa baja dengan diameter luar 50 mm di bungkus dengan insulasi asbes (k = 0,166 W/mK) yang tebalnya 6,4 mm diikuti dengan insulasi fiber-glass (k = 0,0485 W/mK) yang tebalnya 25 mm. Temperatur dinding pipa 393 K dan temperatur luar insulasi 311 K. Hitunglah temperatur interface antara asbes dan fiber-glass.

Penyelesaian,

Dik:

$$r_1 = \frac{50}{2} = 25\,\text{mm} = 0.025\,\text{m};$$

$r_2 = r_1 + 6.4 = 25 + 6.4$
$= 31.4$ mm or 0.0314 m;

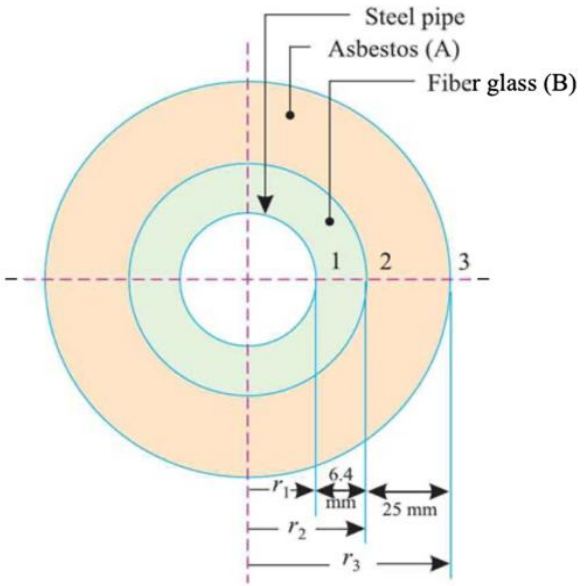
$r_3 = r_2 + 25 = 31.4 + 25$
$= 56.4$ mm $= 0.0564$ m;

$T_1 = 393$ K; $T_3 = 311$ K

$k_A = 0.166$ W/mK;

$k_B = 0.0485$ W/mK.

Skema:



Pers. dasar:

$$Q = \frac{2\pi L(T_1 - T_3)}{\dfrac{\ln(r_2/r_1)}{k_A} + \dfrac{\ln(r_3/r_2)}{k_B}}$$

Hasil:

$$\frac{Q}{L} = \frac{2\pi(T_1 - T_3)}{\dfrac{\ln(r_2/r_1)}{k_A} + \dfrac{\ln(r_3/r_2)}{k_B}}$$

$$= \frac{2\pi(393 - 311)}{\dfrac{\ln(0.0314/0.025)}{0.166} + \dfrac{\ln(0.0564/0.0314)}{0.0485}}$$

$$= \frac{515.22}{1.373 + 12.075} = 38.31\,\text{W/m}$$

Also, $\dfrac{Q}{L} = \dfrac{2\pi(T_1 - T_2)}{\dfrac{\ln(r_2/r_1)}{k_A}}$

or, $38.31 = \dfrac{2\pi(393 - T_2)}{\left[\dfrac{\ln(0.0314/0.025)}{0.166}\right]}$

$$38.31 = \frac{2\pi(393 - T_2)}{1.373}$$

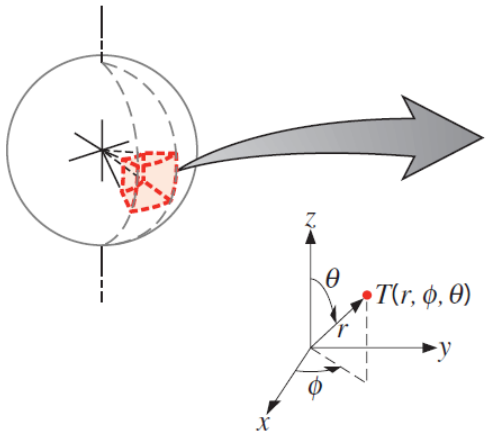
$$\therefore \quad T_2 = 393 - \frac{38.31 \times 1.373}{2\pi} = 384.6\,\text{K}$$

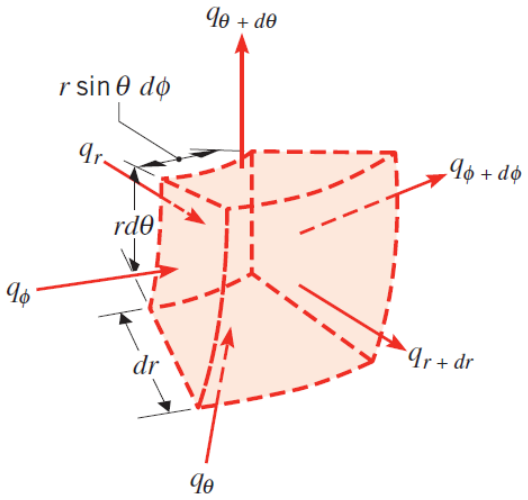
or, $t_2 = 384.6 - 273 = \mathbf{111.6^\circ C}$ **(Ans.)**

3

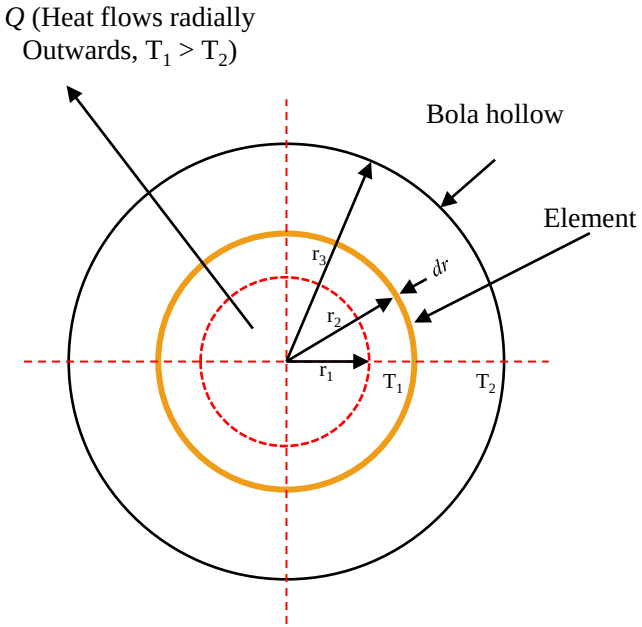
Konduksi panas satu dimensi melalui bejana berbentuk bola hollow dan bola komposit

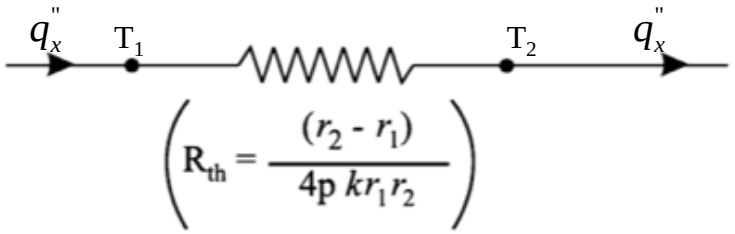
Bola hollow





$$q_r'' = -k\frac{\partial T}{\partial r} \qquad q_\phi'' = -\frac{k}{r}\frac{\partial T}{\partial \phi} \qquad q_z'' = -k\frac{\partial T}{\partial z}$$



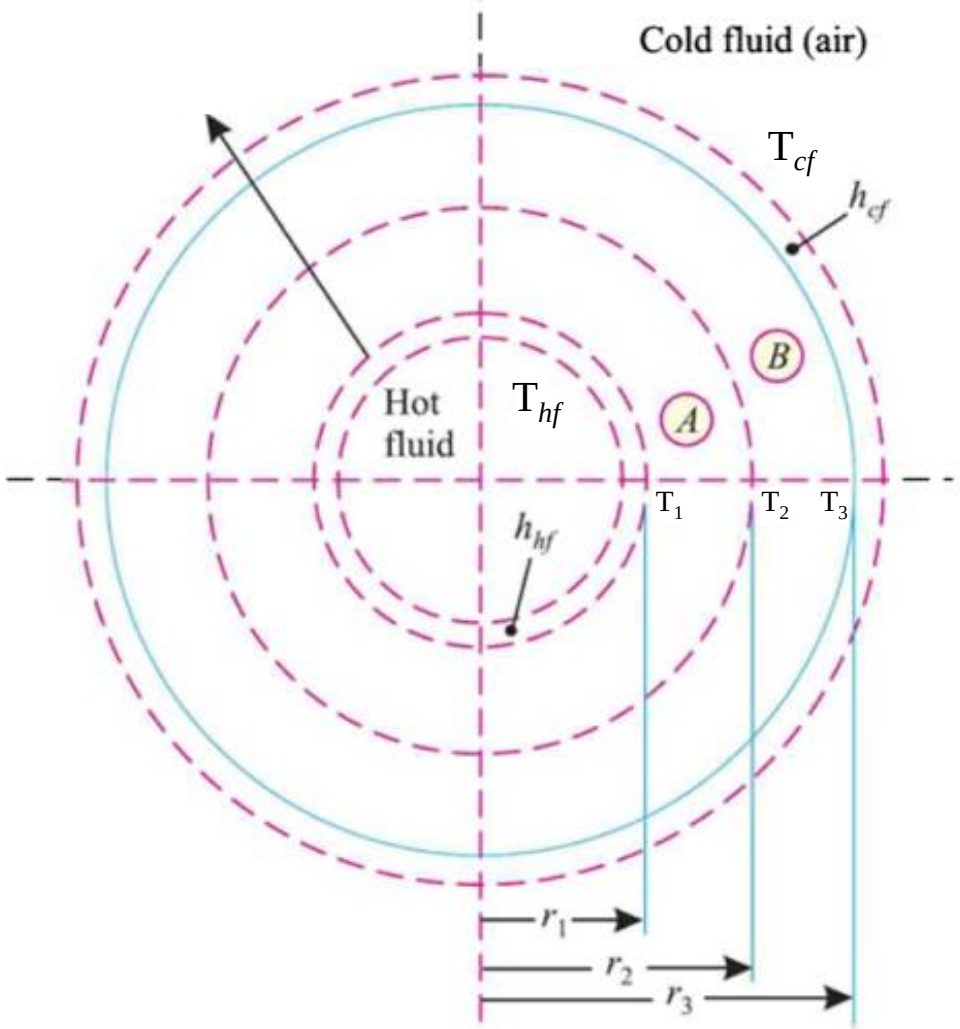


$$q_x'' = \frac{\Delta T}{R_{th}} = \frac{(T_1 - T_2)}{\left[\frac{(r_2 - r_1}{4\pi k r_1 r_2}\right]}$$

3

Konduksi panas satu dimensi melalui bejana berbentuk bola hollow dan bola komposit

Bola hollow komposit



$$q_x^{"} = \frac{4\pi(T_1 - T_{(n+1)})}{\sum_{n=1}^{n=n}\left[\frac{r_{(n+1)} - r_n}{k_n \cdot r_n \cdot r_{(n+1)}}\right]}$$

$$q_x^{"} = \frac{4\pi(T_{hf} - T_{cf})}{\left[\frac{1}{h_{hf} \cdot r_1^2} + \sum_{n=1}^{n=n}\left\{\frac{r_{(n+1)} - r_n}{k_n \cdot r_n \cdot r_{(n+1)}}\right\} + \frac{1}{h_{hf} \cdot r_{(n+1)}^2}\right]}$$

3

Konduksi panas satu dimensi melalui bejana berbentuk bola hollow dan bola komposit

Bola hollow

Contoh 1.1

Suatu bejana (vessel) berbentuk bola yang berdiameter 1,4 m dengan ketebalan 90 mm. Hitunglah laju perpindahan panas jika perbedaan temperature antara permukaan dalam dan luar 220 ^oC. Konduktivitas termal bola 0,083 W/m^oC.

Penyelesaian,

Dik:

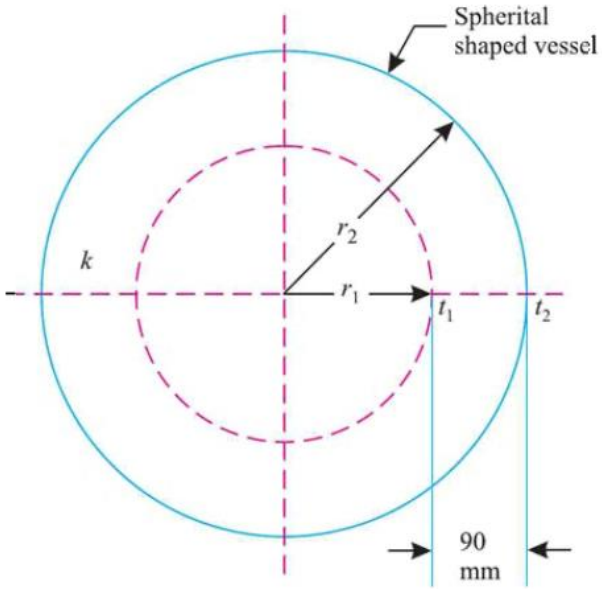
$$r_2 = \frac{1.4}{2} = 0.7\,\text{m.}$$

$$r_1 = 0.7 - \frac{90}{1000} = 0.61\,\text{m}$$

$$t_1 - t_2 = 220°\text{C};$$

$$k = 0.083\ \text{W/m°C}$$

Skema:



Pers. dasar:

$$Q = \frac{(t_1 - t_2)}{\left[\dfrac{(r_2 - r_1)}{4\pi k\, r_1\, r_2}\right]}$$

Hasil:

$$Q = \frac{(t_1 - t_2)}{\left[\dfrac{(r_2 - r_1)}{4\pi k\, r_1\, r_2}\right]} \qquad \text{...Fig. (2.76)}$$

$$= \frac{220}{\left[\dfrac{(0.7 - 0.61)}{4\pi \times 0.083 \times 0.61 \times 0.7}\right]}$$

$$= 1088.67\ \text{W}$$

SPEAKER

3 Konduksi panas satu dimensi melalui bejana berbentuk bola hollow dan bola komposit

Bola hollow komposit

Contoh 1.2

Hitunglah laju perpindahan panas melalui dinding ketel (boiler) berbentuk bola dengan diameter 2 meter dan tebal steel 2 cm (k = 58 W/m°C). Permukaan luar dinding boiler diselubungi dengan asbes (k = 0,116 W/m°C) yang tebalnya 5 mm. Temperatur permukaan luar 50 °C dan fluida di dalam 300 °C. Tahanan film fluida di dalam 0,0023 °C/W.

Penyelesaian:

Dik:

$$r_1 = \frac{2}{2} = 1\,\text{m};\quad r_2 = 1 + \frac{2}{100} = 1.02\,\text{m};\quad k_A = 58\ \text{W/m K};$$

$$k_B = 0.116\ \text{W/m k};\quad r_3 = r_2 + \frac{5}{100} = 1.02 + 0.005 = 0.025\,\text{m}$$

Ditanyakan:

$$Q = \ldots\ldots\ldots ?$$

$Q = h_1 A_1 (t_i - t_1)$ as heat flows from fluid to inner surface by convection only.

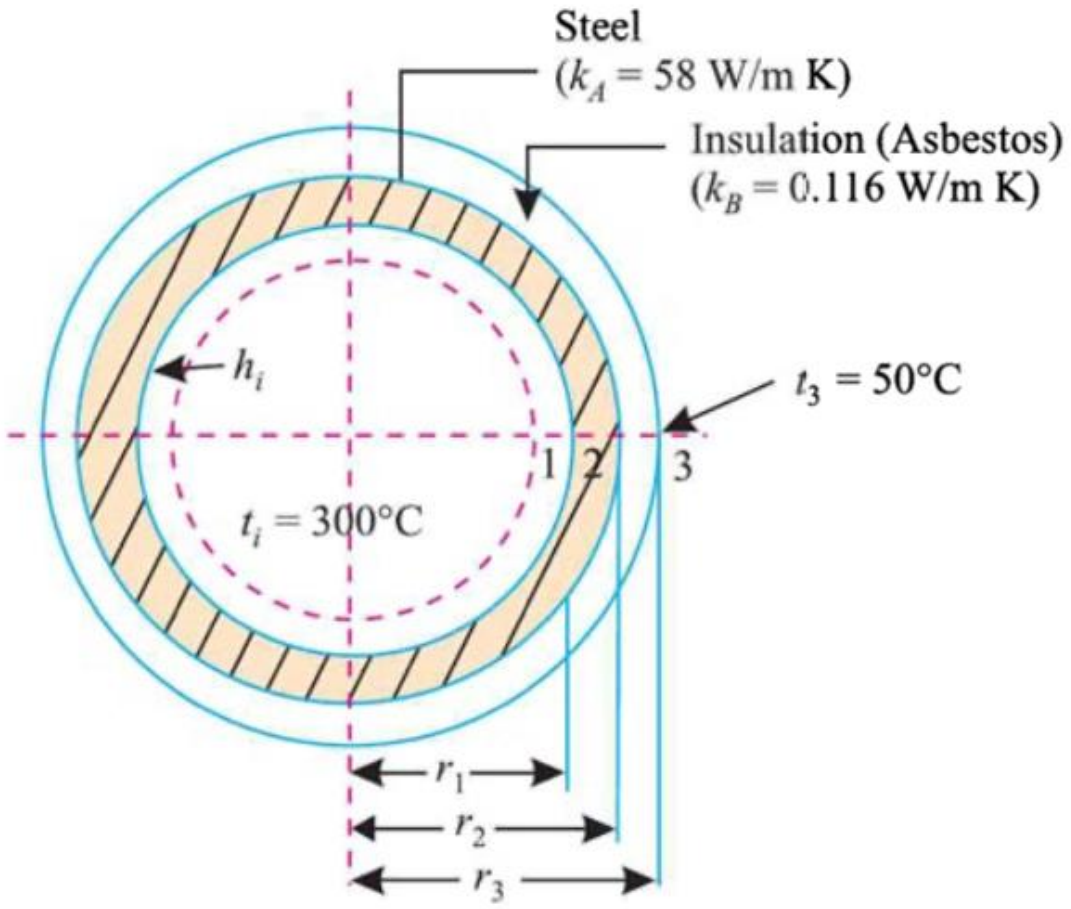
$$Q = \frac{t_i - t_1}{\frac{1}{h_i A_1}}$$

where, $\frac{1}{h_i A_1}$ is inner film resistance.

SPEAKER

3 Konduksi panas satu dimensi melalui bejana berbentuk bola hollow dan bola komposit

Skema:



Pers. dasar:

$$Q = \frac{(t_i - t_3)}{\frac{1}{h_i A_1} + \frac{(r_2 - r_1)}{4\pi k_A r_1 r_2} + \frac{(r_3 - r_2)}{4\pi k_B r_2 r_3}}$$

Hasil:

$$Q = \frac{(300 - 50)}{0.0023 + \frac{(1.02 - 1.0)}{4\pi \times 58 \times 1.0 \times 1.02} + \frac{(1.025 - 1.02)}{4\pi \times 0.116 \times 1.02 \times 1.025}}$$

$$= \frac{250}{0.0023 + 2.6902 \times 10^{-5} + 0.0032808} = 44581\,\text{W} = \mathbf{4.581\,kW}$$

SPEAKER

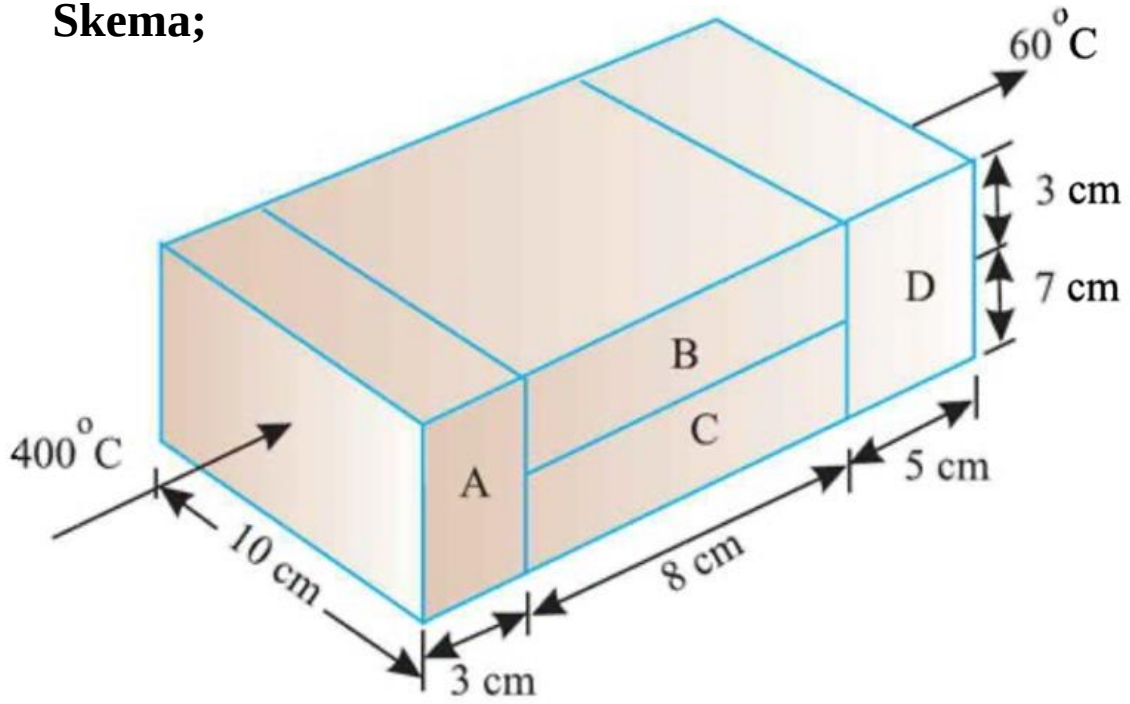
4 Tugas

Tugas 1

1. Hitunglah laju aliran panas yang melalui dinding komposit seperti pada gambar. Asumsi aliran satu dimensi.

$k_A = 150\ W/m°C,$
$k_B = 30\ W/m°C,$
$k_C = 65\ W/m°C,$
$k_D = 50\ W/m°C$

Skema;



4 Tugas

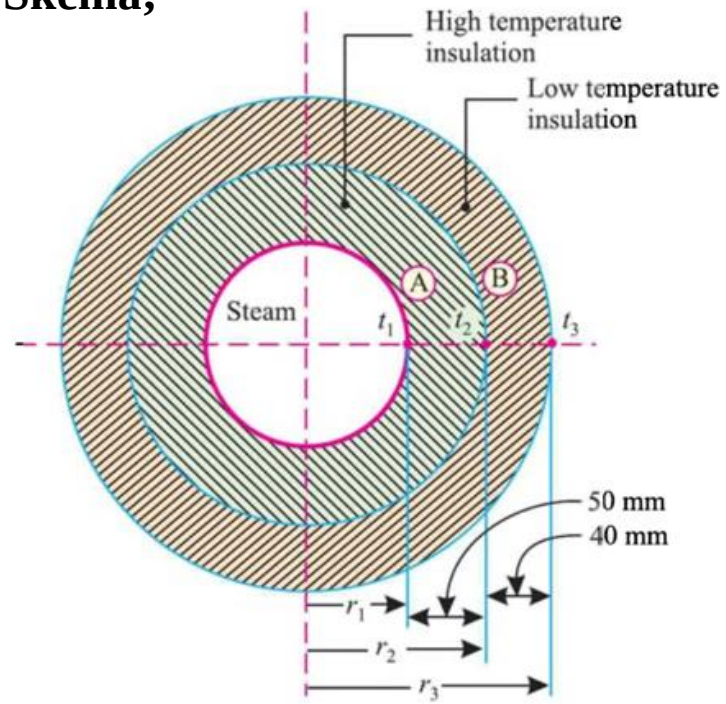
2. Diameter suatu pipa uap 240 mm dan panjang 210 m dilapisi dengan high temperature insulation (k = 0,092 W/m^{o}C) yang tebalnya 50 mm dan low temperatur insulation (k = 0,062 W/m^{o}C). Temperatur permukaan dalam dan luar masing-masing 390 ^{o}C dan 40 ^{o}C.

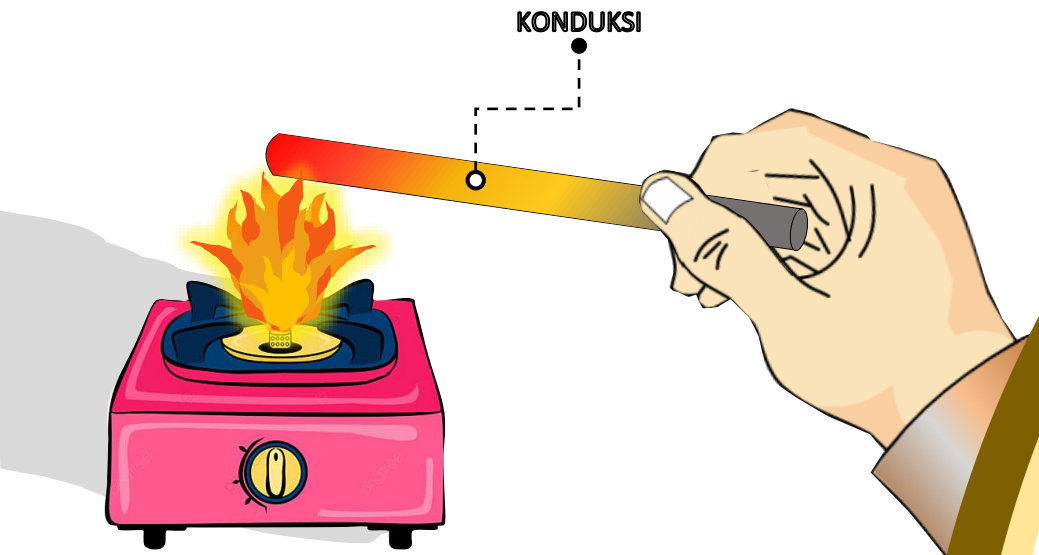
Hitunglah:

(i) Total heat loss per jam.
(ii) Heat loss per m^2 permukaan pipa.
(iii) Total heat loss per m^2 permukaan luar.
(iv) Temperatur antara dua lapisan insulasi.

Abaikan konduksi panas melalui material pipa.

Skema;





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