UNIVERSITI SAINS MALAYSIA

First Semester Examination
Academic Session 2015/2016

December 2015 / January 2016

# EMH 441 – Heat Transfer
## *[Pemindahan Haba]*

Duration : 3 hours
*Masa : 3 jam*

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Please check that this paper contains **NINE** printed pages, **SIXTEEN** page Appendix and **SIX** questions before you begin the examination.

*[sila pastikan bahawa kertas soalan ini mengandungi **SEMBILAN** mukasurat beserta **ENAM BELAS** mukasurat Lampiran dan **ENAM** soalan yang bercetak sebelum anda memulakan peperiksaan.]*

**Appendix**/*Lampiran* :

- Forced convection, Heat Exchanger, Radiation & Air properties [1-16 **page**/*mukasurat*]

**INSTRUCTIONS** : Answer **FIVE** questions.
*[**ARAHAN** : Jawab **LIMA** soalan sahaja.]*

Answer questions in English OR Bahasa Malaysia.
*[Jawab soalan dalam Bahasa Inggeris ATAU Bahasa Malaysia.]*

Answer to each question must begin from a new page.
*[Jawapan bagi setiap soalan mestilah dimulakan pada mukasurat yang baru.]*

In the event of any discrepancies, the English version shall be used.
*[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah diguna pakai.]*

**NOTE:**
Provided: Formula Booklet
*Dibekalkan: Buku formula*

**Q1. [a] How heat is transferred by the followings, and use one example (for each case) to explain the concept.**

*Bagaimana pemindahan haba berlaku seperti berikut, gunakan satu contoh (bagi setiap kes) untuk penerangan.*

**[i] Conduction**
*Konduksi*

(**20 marks**/*markah*)

**[ii] Convection**
*Perolakan*

(**20 marks**/*markah*)

**[iii] Radiation**
*Sinaran*

(**20 marks**/*markah*)

**[b] On a hot day, a student turns his fan on when he leaves his room in the morning. When he returns in the evening, explain whether his room will be warmer or cooler than the neighboring rooms. Assume all the doors and windows are kept closed.**

*Pada suatu hari yang panas, seorang pelajar hidupkan satu kipas semasa dia keluar dari bilik masa pagi. Semasa beliau balik masa senja, terangkan samada bilik beliau akan menjadi lebih panas atau sejuk berbanding dengan bilik jiran. Andaikan semua pintu dan tingkap tertutup.*

(**20 marks**/*markah*)

**[c] Consider two identical rooms, one with a stand-alone air cooler unit in it and the other without one. If all the doors and windows are closed, explain whether the room that contains the air cooler be cooler or warmer than the other room.**

*Pertimbangkan dua bilik yang serupa, satu bilik mempunyai sebuah penyejuk udara kendiri di dalamnya dan satu lagi bilik tiada. Jika semua pintu dan tingkap adalah tertutup, terangkan samada bilik yang mempunyai penyejuk udara jadi lebih sejuk atau lebih panas berbanding dengan satu lagi bilik.*

(**20 marks**/*markah*)

**Q2. [a] Given a cylinder with length of 1m, outer diameter of 0.25m, wall thickness of 0.05m;**

Diberikan s*atu silinder dengan panjang 1m, diameter luar 0.25m, tebal dinding 0.05m;*

**[i] Derive an equation for conductive heat transfer of a cylinder.**

*Terbitkan satu persamaan konduksi untuk sebuah silinder.*

**[ii] If the surface temperature is 80°C, ambient temperature is 30°C, calculate the percentage of reduction of heat loss from the cylinder surface when a 0.05m insulation (k = 0.2 W/m°C) is used. Coefficient of heat transfer is 8 W/m$^2$°C.**

*Jika suhu permukaan ialah 80°C, suhu ambien ialah 30°C, kirakan peratus pengurangan bagi kehilangan haba dari permukaan silinder apabila satu penebat (k = 0.2 W/m°C) setebal 0.05m digunakan. Pekali pemindahan haba ialah 8 W/m$^2$°C.*

(**60 marks**/*markah*)

**[b] A heat source of 2 kW is placed at the center of a sphere, the conductivity of the sphere is 15 W/m.K, and diameter of the sphere is 70 cm.**

*Satu sumber panas 2kW diletakkan di tengah satu sfera, kekonduksian sfera ialah 15 W/m.K, dan diameter sfera ialah 70cm.*

**[i] Derive an equation for surface temperature estimation of a sphere.**

*Terbitkan satu persamaan untuk pengiraan suhu permukaan sfera.*

**[ii] If the ambient temperature is 30°C, calculate the surface and center temperatures of the sphere. Coefficient of heat transfer is 8 W/m$^2$°C.**

*Jika suhu ambien ialah 30°C, kirakan suhu permukaan dan suhu tengah sfera. Pekali pemindahan haba ialah 8 W/m$^2$°C.*

(**40 marks**/*markah*)

**Q3. [a] Air flow through a long rectangular heating duct that is 0.75m wide and 0.25m high maintains the outer duct surface at 45°C. If the bottom surface of the duct is insulated, and the three non-insulated surfaces are exposed to air at 15°C in the crawlspace beneath a home, calculate the heat loss from the duct per meter length.**
**Given, air ($T_f$ = 303K): $v = 16.2 \times 10^{-6}$ m²/s, $\alpha = 22.9 \times 10^{-6}$ m²/s, $k$ = 0.0265 W/m.K, $\beta$ = 0.0033 K$^{-1}$, $Pr$ = 0.71.**

*Udara mengalir dalam satu salur segiempat yang panjang berlebar 0.75m dan tinggi 0.25m mempunyai suhu permukaan luar 45°C. Jika permukaan bawah salur ditebatkan, dan tiga permukaan yang tidak ditebatkan didedahkan ke udara 15°C dalam ruang merangkak di bawah sebuah rumah, kirakan kehilangan haba dari salur per meter panjang.*
*Diberi, udara ($T_f$ = 303K): $v = 16.2 \times 10^{-6}$ m²/s, $\alpha = 22.9 \times 10^{-6}$ m²/s, k = 0.0265 W/m.K, $\beta$ = 0.0033 K$^{-1}$, Pr = 0.71.*

(**60 marks**/*markah*)

**[b] A horizontal high pressure refrigerant pipe of 0.01m outer diameter passes through a large room whose wall and air temperature are 30°C. The pipe has an outside surface temperature of 0°C. Calculate the heat transfer from air to the pipe per unit length. Given, air ($T_f$ = 288K): $v = 14.82 \times 10^{-6}$ m²/s, $\alpha = 20.92 \times 10^{-6}$ m²/s, $k$ = 0.0253 W/m.K, $\beta$ = 0.0035 K$^{-1}$, $Pr$ = 0.71.**

*Satu paip bahan penyejuk yang mempunyai diameter luar 0.01m melalui satu bilik yang besar dimana suhu dinding dan udaranya ialah 30°C. Paip tersebut mempunyai suhu permukaan luar 0°C. Kirakan pemindahan haba dari udara ke paip per unit panjang. Diberi, udara ($T_f$ = 303K): $v = 16.2 \times 10^{-6}$ m²/s, $\alpha = 22.9 \times 10^{-6}$ m²/s, k = 0.0265 W/m.K, $\beta$ = 0.0033 K$^{-1}$, Pr = 0.71.*

(**40 marks**/*markah*)

**Q4.** **[a]** **Define and write the equations of Reynolds and Nusselts numbers.**

*Takrif dan tuliskan persamaan-persamaan Nombor Reynolds dan Nombor Nusselts.*

(**10 marks**/*markah*)

**[b]** **An air chamber as shown in Figure Q4[b] is employed to cool 15cm x 15cm flat plate at normal ambient pressure. The manometer is used to measure air pressure inside the air chamber. The distance between two manometer fluid levels is 6.37mm. Given, ambient temperature is 25°C, flat plate temperature is 95°C and manometer fluid density is 800kg/m$^3$.**

*Sebuah kebuk udara seperti Rajah S4[b] digunakan untuk menyejukkan plat rata 15sm x 15sm dalam tekanan persekitaran normal. Sebuah manometer telah digunakan untuk mengira tekanan udara di dalam kebuk udara. Jarak antara dua aras permukaan bendalir manometer adalah 6.37mm. Diberi, suhu ambien ialah 25°C, suhu plat rata ialah 95°C dan ketumpatan bendalir manometer ialah 800kg/m$^3$.*

**[i]** **Calculate the air velocity exit from the air chamber to flat plate.**
*Kirakan halaju udara keluar dari kebuk udara ke plat rata.*

**[ii]** **Calculate heat transfer from flat plate to surrounding.**
*Kirakan kadar pemindahan haba dari plat rata ke persekitaran.*

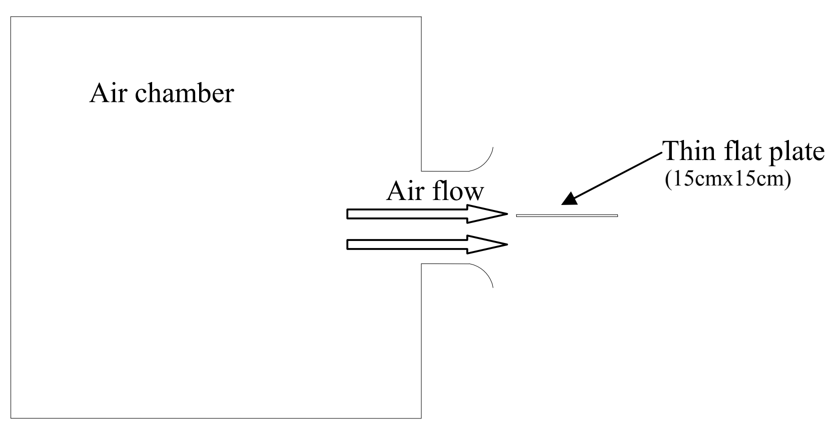



**Figure Q4[b]**
*Rajah S4(b)*

(**60 marks**/*markah*)

**[c] Water ($c_p$=4180 J/kg.K) is utilized to cool hot oil ($c_p$=2200 J/kg.K) in heat exchanger as shown in Figure Q4[c]. The tubes are thin with a diameter of 2.0cm. The length of each tube pass in the heat exchanger is 3m, and overall heat transfer coefficient is 340 W/m$^2$.K. Water flows through the tubes at a rate of 0.1 kg/s, and the oil through the shell at a rate of 0.2 kg/s. The oil and water inlet temperature are 180°C and 20°C respectively. Calculate:**

*Air ($c_p$=4180 J/kg.K) digunakan untuk menyejukkan minyak panas ($c_p$=2200 J/kg.K) dalam penukar haba seperti Rajah S4[c]. Tiub adalah nipis dengan diameter 2.0cm. Panjang setiap tiub laluan dalam penukar haba adalah 3m, dan pekali pemindahan haba adalah 340 W/m$^2$.K. Air mengalir melalui tiub-tiub pada kadar 0.1kg/s dan minyak mengalir melalui petala pada kadar 0.2kg/s. Suhu masukan minyak ialah 180°C dan suhu masukan air 20°C. Kirakan:*

**[i] Rate of heat transfer.**
*Kadar pemindahan haba.*

**[ii] Water outlet temperature.**
*Suhu air keluaran.*

**[iii] Oil outlet temperature.**
*Suhu minyak keluaran.*

(**30 marks**/*markah*)

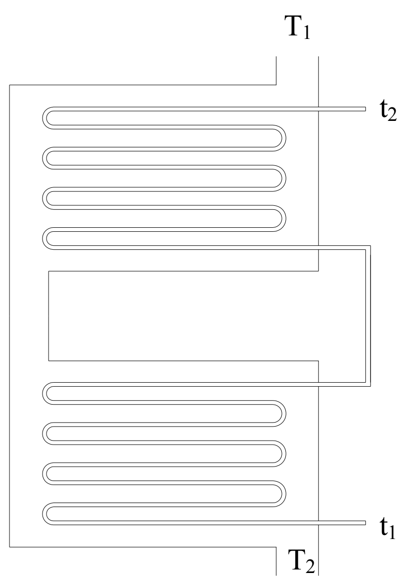



**Figure Q4[c]**
*Rajah S4(c)*

**Q5.** **[a]** **Define the definition of area density. Give TWO differences between condenser heat exchanger and boiler heat exchanger.**

*Takrifkan definasi ketumpatan kawasan. Berikan DUA perbezaan antara kondensor penukar haba dan dandang penukar haba.*

(**10 marks**/*markah*)

**[b]** **A 20cm aluminium ball ($\rho$=2700 kg/m$^3$, $c_p$=920 J/kg.K) is removed from an oven at uniform temperature of 290°C to a wind tunnel at ambient temperature of 15°C, as shown in Figure Q5[b]. The distance between two manometer fluid levels is 1.95mm. The surface ball temperature eventually drops to 210°C. Calculate the average convection heat transfer coefficient during this cooling process and calculate how long the process will take. Given manometer fluid density is 800kg/m$^3$.**

*Sebuah bola aluminium 20cm ($\rho$=2700 kg/m$^3$, $c_p$=920 J/kg.K) dikeluarkan dari oven pada suhu seragam 290°C ke dalam terowong angin pada suhu persekitaran 15°C, seperti Rajah S5[b]. Jarak di antara dua aras permukaan bendalir manometer ialah 1.95mm. Suhu permukaan bola kemudiannya berkurang kepada 210°C. Kirakan purata perolakan pekali pemindahan haba semasa proses penyejukan dan kirakan masa yang diambil untuk proses penyejukan ini. Diberi ketumpatan bendalir manometer ialah 800kg/m$^3$.*

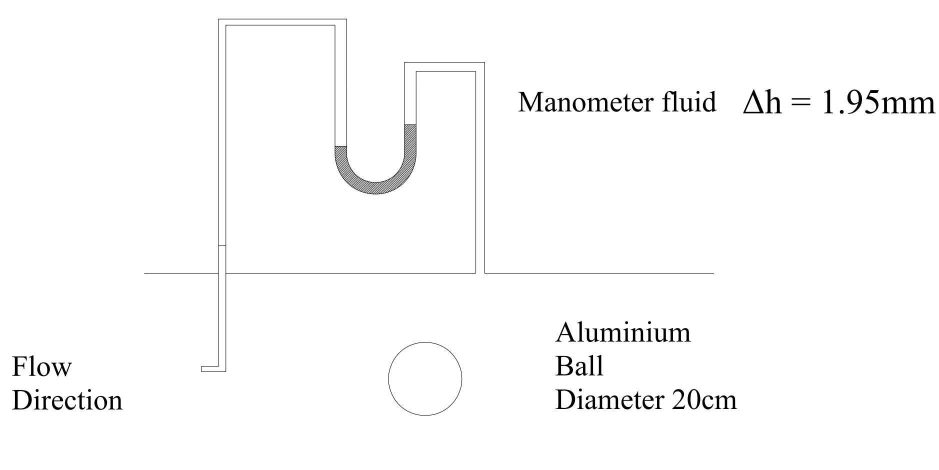



**Figure Q5[b]**
*Rajah S5[b]*

(**60 marks**/*markah*)

**[c]** **A heat exchanger is tested in order to determine performance of heat exchanger as shown in Figure Q5[c]. This heat exchanger has 20 tubes and each tube has internal diameter = 1.5cm and length = 2m. The cold water (Cp=4180 J/kg.K) enters the tubes at 30°C at rate of 3kg/s and leaves at 65°C. Oil (Cp=2150 J/kg.K) enters through the shell and is cooled from 80°C to 45°C. Calculate the overall heat transfer coefficient of this heat exchanger.**

*Sebuah penukar haba telah diuji untuk mengukur prestasi penukar haba seperti Rajah S5[c]. Penukar haba ini mempunyai 20 tiub-tiub dan setiap tube mempunyai diameter dalaman = 1.5sm dan panjang = 2m. Air sejuk (Cp=4180 J/kg.K) memasuki tiub pada 30°C pada kadar 3kg/s dan keluar pada 65°C. Minyak (Cp=2150 J/kg.K) memasuki petala dan disejukkan dari 80°C kepada 45°C. Kirakan pekali pemindahan haba keseluruhan untuk penukar haba ini.*

(**30 marks**/*markah*)

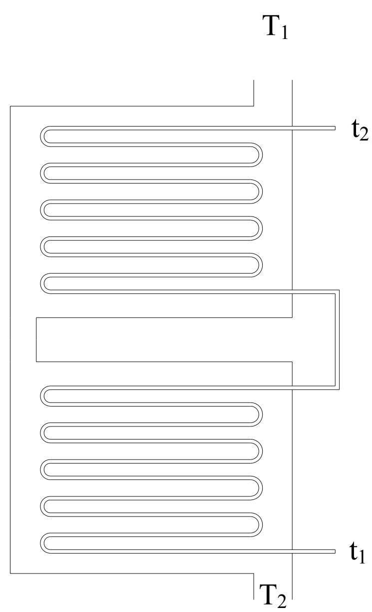



**Figure Q5[c]**
*Rajah S5[c]*

**Q6. [a] Define the following in radiation heat transfer:**
*Takrifkan perkara-perkara berikut dalam radiasi pemindahan haba:*

**[i] Emissivity.**
*Pancaran .*

**[ii] Spectral emissivity.**
*Pancaran spectra.*

**[iii] View factor.**
*Faktor pandangan.* (**15 marks**/*markah*)

**[b] A star may be treated as a blackbody with the surface temperature of 6200K at a mean distance ($r_{orbit}$) of 2 x $10^{11}$m from a planet. The diameters of the star and the planet are 2 x $10^9$m and 13 x $10^6$m respectively. Given Boltzmann's constant is 5.67 x $10^{-8}$. Calculate:**

*Sebuah bintang yang boleh dianggap sebagai jasad hitam mempunyai suhu permukaan ialah 6200K pada jarak purata ($r_{orbit}$) ialah 2 x $10^{11}$ dari sebuah planet. Diameter bintang ialah 2 x $10^9$m dan diameter planet ialah 13 x $10^6$m Diberi pekali Boltzmann ialah 5.67 x $10^{-8}$. Kirakan:*

**[i] Total energy emitted by the star.**
*Jumlah tenaga yang dipancarkan oleh bintang.*

**[ii] Emission absorbed per $m^2$, outside the planet surface.**
*Pemancaran yang diserap per $m^2$, pada permukaan luar planet.*

**[iii] Total energy received by the planet.**
*Jumlah tenaga diterima oleh planet.* (**45 marks**/*markah*)

**[c] Air stream at 30°C flows at 0.5 m/s across a 100W bulb with surface temperature of 120°C. If the bulb is approximated by a 50mm diameter sphere, calculate the heat transfer rate and the percentage of power loss due to convection. Use the correlation:**

*Aliran udara pada 30°C mengalir pada 0.5 m/s melintasi sebuah mentol 100W dengan suhu permukaan 120°C. Sekiranya mentol tersebut mempunyai anggaran diameter ialah 50mm, kirakan kadar pemindahan haba dan peratusan tenaga hilang disebabkan oleh perolakan. Guna korelasi:*

$$Nu_{ave} = 0.37\ Re_D^{0.6}$$

(**40 marks**/*markah*)

**-oooOooo-**

**APPENDIX**
*LAMPIRAN*

**Appendix 1 (Forced convection)**

*Laminar*: $$\mathrm{Nu}_x = \frac{h_x x}{k} = 0.332\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{1/3} \qquad \mathrm{Pr} > 0.6$$

*Turbulent*: $$\mathrm{Nu}_x = \frac{h_x x}{k} = 0.0296\,\mathrm{Re}_x^{0.8}\,\mathrm{Pr}^{1/3} \qquad 0.6 \le \mathrm{Pr} \le 60, \quad 5 \times 10^5 \le \mathrm{Re}_x \le 10^7$$

*Laminar*: $$\mathrm{Nu} = \frac{hL}{k} = 0.664\,\mathrm{Re}_L^{0.5}\,\mathrm{Pr}^{1/3} \qquad \mathrm{Re}_L < 5 \times 10^5$$

*Turbulent*: $$\mathrm{Nu} = \frac{hL}{k} = 0.037\,\mathrm{Re}_L^{0.8}\,\mathrm{Pr}^{1/3} \qquad 0.6 \le \mathrm{Pr} \le 60, \quad 5 \times 10^5 \le \mathrm{Re}_L \le 10^7$$

## Flat Plate with Unheated Starting Length

*Laminar*: $$\mathrm{Nu}_x = \frac{\mathrm{Nu}_{x\,(\text{for } \xi = 0)}}{[1 - (\xi/x)^{3/4}]^{1/3}} = \frac{0.332\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{1/3}}{[1 - (\xi/x)^{3/4}]^{1/3}}$$

*Turbulent*: $$\mathrm{Nu}_x = \frac{\mathrm{Nu}_{x\,(\text{for } \xi = 0)}}{[1 - (\xi/x)^{9/10}]^{1/9}} = \frac{0.0296\,\mathrm{Re}_x^{0.8}\,\mathrm{Pr}^{1/3}}{[1 - (\xi/x)^{9/10}]^{1/9}}$$

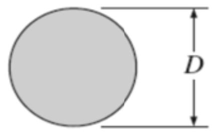
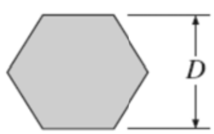
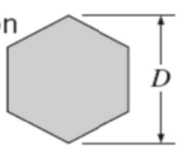
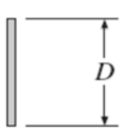
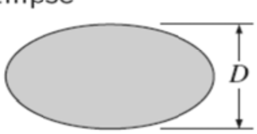
## Uniform/Constant Heat Flux

*Laminar:* $$\mathrm{Nu}_x = 0.453\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{1/3} \qquad \mathrm{Pr} > 0.6, \qquad \mathrm{Re}_x < 5 \times 10^5$$

*Turbulent:* $$\mathrm{Nu}_x = 0.0308\,\mathrm{Re}_x^{0.8}\,\mathrm{Pr}^{1/3} \qquad 0.6 \le \mathrm{Pr} \le 60, \qquad 5 \times 10^5 \le \mathrm{Re}_x \le 10^7$$

## Appendix 1 (Forced convection)

Empirical correlations for the average Nusselt number for forced convection over circular and noncircular cylinders in cross flow (from Zukauskas, 1972 and Jakob, 1949)

| Cross-section of the cylinder | Fluid | Range of Re | Nusselt number |
|---|---|---|---|
| Circle   | Gas or liquid | 0.4–4<br>4–40<br>40–4000<br>4000–40,000<br>40,000–400,000 | $Nu = 0.989Re^{0.330}\ Pr^{1/3}$<br>$Nu = 0.911Re^{0.385}\ Pr^{1/3}$<br>$Nu = 0.683Re^{0.466}\ Pr^{1/3}$<br>$Nu = 0.193Re^{0.618}\ Pr^{1/3}$<br>$Nu = 0.027Re^{0.805}\ Pr^{1/3}$ |
| Square   | Gas | 5000–100,000 | $Nu = 0.102Re^{0.675}\ Pr^{1/3}$ |
| Square (tilted 45°)   | Gas | 5000–100,000 | $Nu = 0.246Re^{0.588}\ Pr^{1/3}$ |
| Hexagon   | Gas | 5000–100,000 | $Nu = 0.153Re^{0.638}\ Pr^{1/3}$ |
| Hexagon (tilted 45°)   | Gas | 5000–19,500<br>19,500–100,000 | $Nu = 0.160Re^{0.638}\ Pr^{1/3}$<br>$Nu = 0.0385Re^{0.782}\ Pr^{1/3}$ |
| Vertical plate   | Gas | 4000–15,000 | $Nu = 0.228Re^{0.731}\ Pr^{1/3}$ |
| Ellipse   | Gas | 2500–15,000 | $Nu = 0.248Re^{0.612}\ Pr^{1/3}$ |

**Appendix 1 (Forced convection)**

For flow over a *sphere*

$$\mathrm{Nu_{sph}} = \frac{hD}{k} = 2 + [0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3}]\,\mathrm{Pr}^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

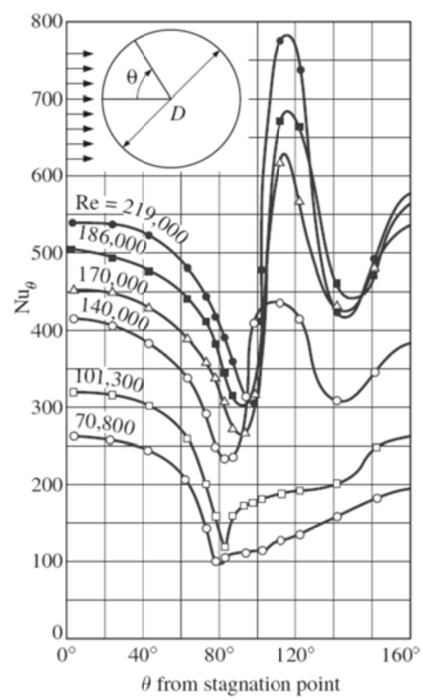
$3.5 \le \mathrm{Re} \le 80{,}000$ and $0.7 \le \mathrm{Pr} \le 380$

The fluid properties are evaluated at the free-stream temperature $T_\infty$, except for $\mu_s$, which is evaluated at the surface temperature $T_s$.

For flow over a *cylinder*

$$\mathrm{Nu_{cyl}} = \frac{hD}{k} = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{[1 + (0.4/\mathrm{Pr})^{2/3}]^{1/4}}\left[1 + \left(\frac{\mathrm{Re}}{282{,}000}\right)^{5/8}\right]^{4/5} \quad \mathrm{RePr} > 0.2$$

The fluid properties are evaluated at the *film temperature* $T_f = \frac{1}{2}(T_\infty + T_s)$



**Appendix 2 (Heat Exchanger)**

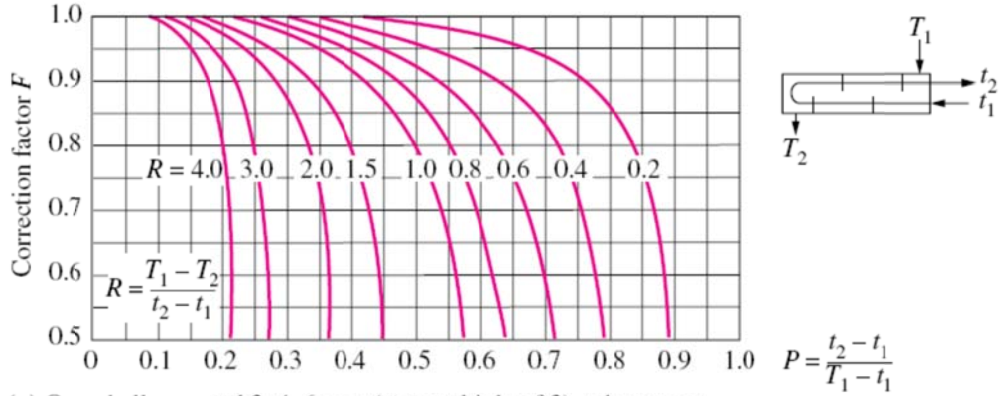
$$\dot{Q} = \dot{m}_h \, c_{ph} \, \Delta T_h$$
$$= \dot{m}_c \, c_{pc} \, \Delta T_c$$

$$\dot{Q} = UA_s \, \Delta T_{\text{lm}}$$

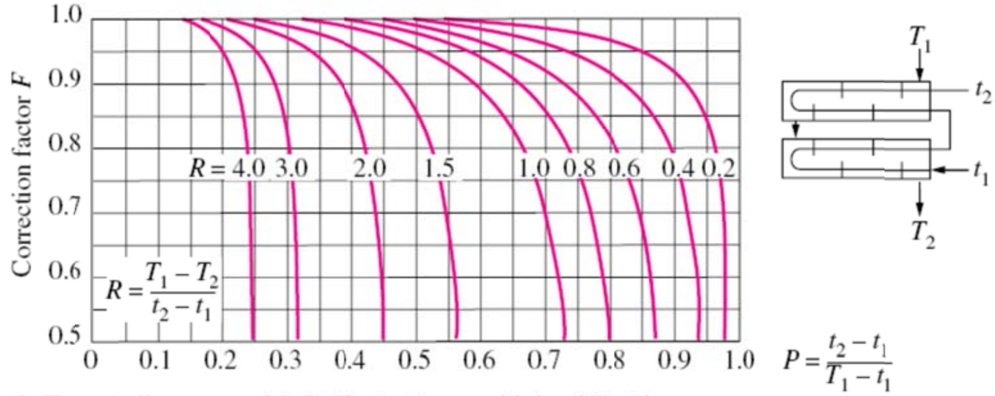
$$C_c = \dot{m}_c c_{pc}$$

$$\Delta T_{\text{lm}} = \frac{\Delta T_1 - \Delta T_2}{\ln (\Delta T_1 / \Delta T_2)}$$ log mean temperature difference

$$\Delta T_{\text{lm}} = F \, \Delta T_{\text{lm, CF}}$$

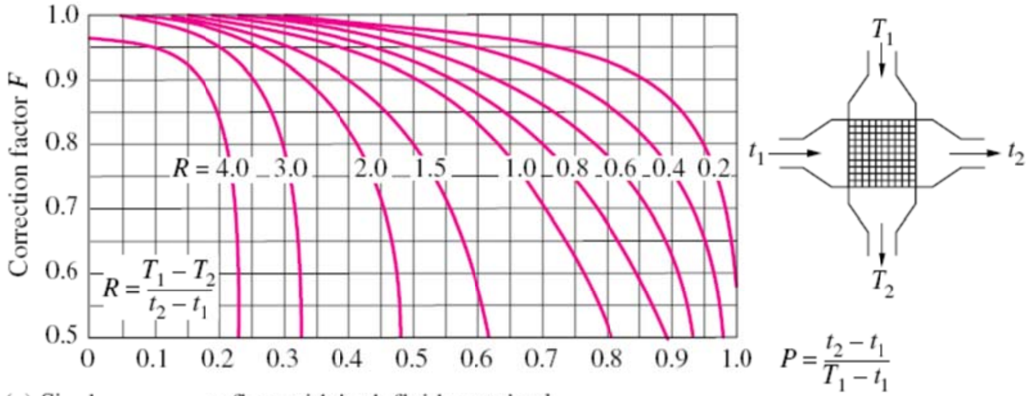



(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes

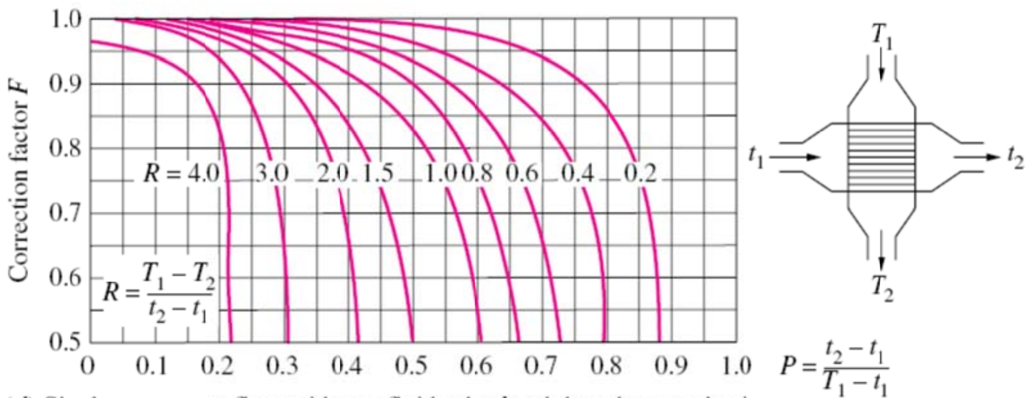



(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes

**Appendix 2 (Heat Exchanger)**




(*c*) Single-pass cross-flow with both fluids *unmixed*




(*d*) Single-pass cross-flow with one fluid *mixed* and the other *unmixed*

$$\dot{Q}_{\max} = C_{\min}(T_{h,\,\mathrm{in}} - T_{c,\,\mathrm{in}})$$

$$\Delta T_{\max} = T_{h,\,\mathrm{in}} - T_{c,\,\mathrm{in}}$$

$$\varepsilon_{\text{parallel flow}} = \frac{1 - \exp\left[-\frac{UA_s}{C_{\min}}\left(1 + \frac{C_{\min}}{C_{\max}}\right)\right]}{1 + \frac{C_{\min}}{C_{\max}}}$$

# Appendix 2 (Heat Exchanger)

**TABLE 11–4**

Effectiveness relations for heat exchangers: NTU = $UA_s/C_{min}$ and $c = C_{min}/C_{max} = (\dot{m}c_p)_{min}/(\dot{m}c_p)_{max}$

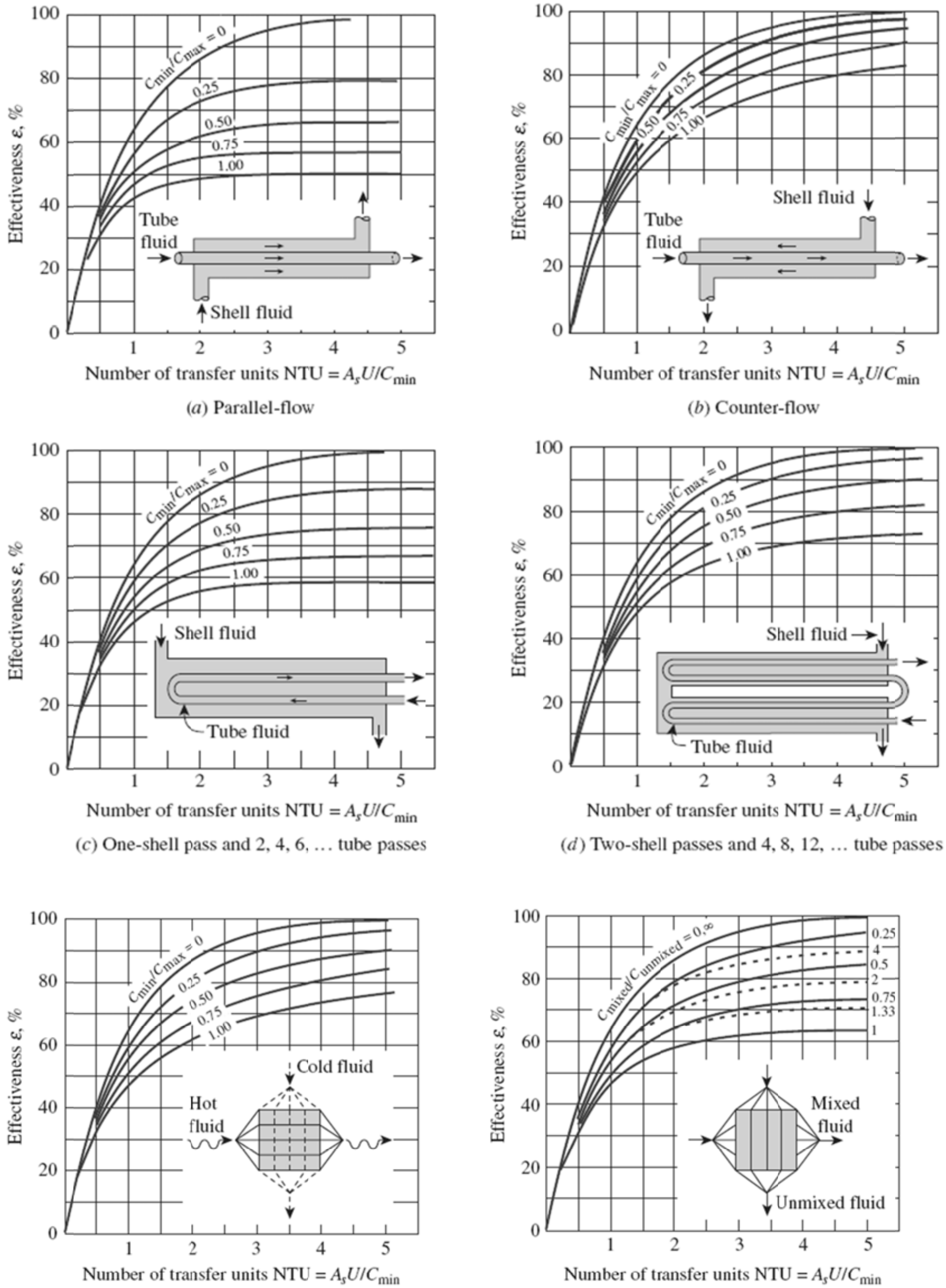
| Heat exchanger type | Effectiveness relation |
|---|---|
| 1 *Double pipe:* | |
| Parallel-flow | $\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 + c)]}{1 + c}$ |
| Counter-flow | $\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1 - c)]}{1 - c\exp[-\text{NTU}(1 - c)]}$ |
| 2 *Shell-and-tube:* One-shell pass 2, 4,…tube passes | $\varepsilon = 2\left\{1 + c + \sqrt{1 + c^2}\dfrac{1 + \exp[-\text{NTU}\sqrt{1 + c^2}]}{1 - \exp[-\text{NTU}\sqrt{1 + c^2}]}\right\}^{-1}$ |
| 3 *Cross-flow* (*single-pass*) Both fluids unmixed | $\varepsilon = 1 - \exp\left\{\dfrac{\text{NTU}^{0.22}}{c}[\exp(-c\ \text{NTU}^{0.78}) - 1]\right\}$ |
| $C_{max}$ mixed, $C_{min}$ unmixed | $\varepsilon = \dfrac{1}{c}(1 - \exp\{-c[1 - \exp(-\text{NTU})]\})$ |
| $C_{min}$ mixed, $C_{max}$ unmixed | $\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\ \text{NTU})]\right\}$ |
| 4 *All heat exchangers with c = 0* | $\varepsilon = 1 - \exp(-\text{NTU})$ |

**TABLE 11–5**

NTU relations for heat exchangers: $NTU = UA_s/C_{min}$ and $c = C_{min}/C_{max} = (\dot{m}c_p)_{min}/(\dot{m}c_p)_{max}$

| Heat exchanger type | NTU relation |
|---|---|
| 1 *Double-pipe:* | |
| Parallel-flow | $NTU = -\dfrac{\ln[1-\varepsilon(1+c)]}{1+c}$ |
| Counter-flow | $NTU = \dfrac{1}{c-1}\ln\left(\dfrac{\varepsilon-1}{\varepsilon c-1}\right)$ |
| 2 *Shell and tube:* One-shell pass 2, 4,…tube passes | $NTU = -\dfrac{1}{\sqrt{1+c^2}}\ln\left(\dfrac{2/\varepsilon-1-c-\sqrt{1+c^2}}{2/\varepsilon-1-c+\sqrt{1+c^2}}\right)$ |
| 3 *Cross-flow (single-pass):* $C_{max}$ mixed, $C_{min}$ unmixed | $NTU = -\ln\left[1+\dfrac{\ln(1-\varepsilon c)}{c}\right]$ |
| $C_{min}$ mixed, $C_{max}$ unmixed | $NTU = -\dfrac{\ln[c\ln(1-\varepsilon)+1]}{c}$ |
| 4 *All heat exchangers with $c = 0$* | $NTU = -\ln(1-\varepsilon)$ |

## Appendix 2 (Heat Exchanger)




(a) Parallel-flow

(b) Counter-flow

(c) One-shell pass and 2, 4, 6, … tube passes

(d) Two-shell passes and 4, 8, 12, … tube passes

(e) Cross-flow with both fluids unmixed

(f) Cross-flow with one fluid mixed and the other unmixed

**FIGURE 11–26**
Effectiveness for heat exchangers.

**Appendix 2 (Heat Exchanger)**

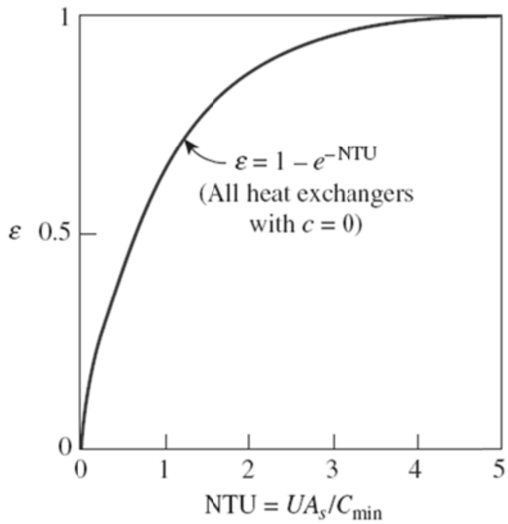



**FIGURE 11–28**

The effectiveness relation reduces to $\varepsilon = \varepsilon_{\max} = 1 - \exp(-\text{NTU})$ for all heat exchangers when the capacity ratio $c = 0$.

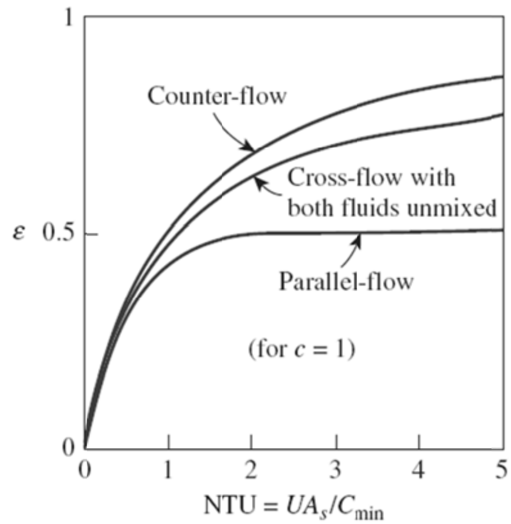


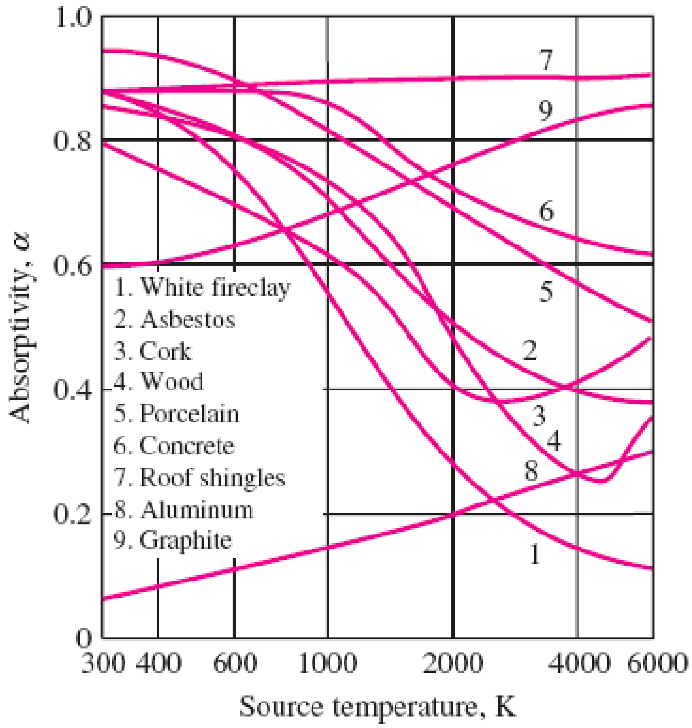

**FIGURE 11–27**

For a specified NTU and capacity ratio $c$, the counter-flow heat exchanger has the highest effectiveness and the parallel-flow the lowest.

**Appendix 3 (Radiation)**

$$E_{emit} = \varepsilon \sigma T^4$$

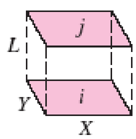
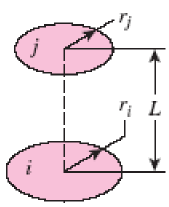
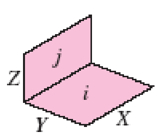
Black Body $E_b(T) = \sigma T^4$ $(W/m^2)$



# Appendix 3 (Radiation)

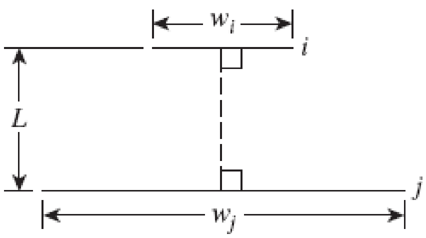
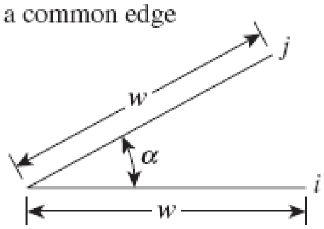
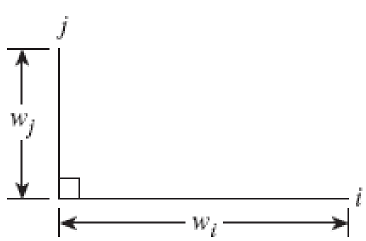
**TABLE 13–1**

View factor expressions for some common geometries of finite size (3-D)

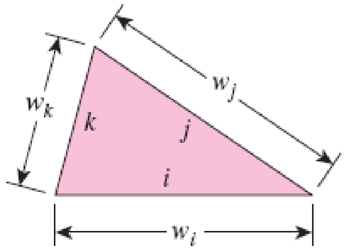
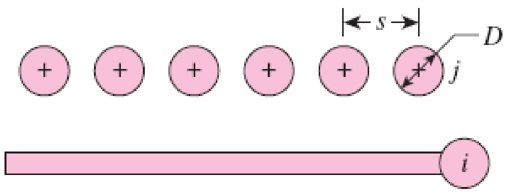
| Geometry | Relation |
|---|---|
| Aligned parallel rectangles   | $\bar{X} = X/L$ and $\bar{Y} = Y/L$ <br> $F_{i \to j} = \frac{2}{\pi \bar{X} \bar{Y}} \left\{ \ln \left[ \frac{(1+\bar{X}^2)(1+\bar{Y}^2)}{1+\bar{X}^2+\bar{Y}^2} \right]^{1/2} + \bar{X}(1+\bar{Y}^2)^{1/2} \tan^{-1} \frac{\bar{X}}{(1+\bar{Y}^2)^{1/2}} + \bar{Y}(1+\bar{X}^2)^{1/2} \tan^{-1} \frac{\bar{Y}}{(1+\bar{X}^2)^{1/2}} - \bar{X} \tan^{-1} \bar{X} - \bar{Y} \tan^{-1} \bar{Y} \right\}$ |
| Coaxial parallel disks   | $R_i = r_i/L$ and $R_j = r_j/L$ <br> $S = 1 + \frac{1+R_j^2}{R_i^2}$ <br> $F_{i \to j} = \frac{1}{2} \left\{ S - \left[ S^2 - 4 \left( \frac{r_j}{r_i} \right)^2 \right]^{1/2} \right\}$ <br> For $r_i = r_j = r$ and $R = r/L$: $F_{i \to j} = F_{j \to i} = 1 + \frac{1 - \sqrt{4R^2+1}}{2R^2}$ |
| Perpendicular rectangles with a common edge   | $H = Z/X$ and $W = Y/X$ <br> $F_{i \to j} = \frac{1}{\pi W} \left( W \tan^{-1} \frac{1}{W} + H \tan^{-1} \frac{1}{H} - (H^2+W^2)^{1/2} \tan^{-1} \frac{1}{(H^2+W^2)^{1/2}} + \frac{1}{4} \ln \left\{ \frac{(1+W^2)(1+H^2)}{1+W^2+H^2} \left[ \frac{W^2(1+W^2+H^2)}{(1+W^2)(W^2+H^2)} \right]^{W^2} \times \left[ \frac{H^2(1+H^2+W^2)}{(1+H^2)(H^2+W^2)} \right]^{H^2} \right\} \right)$ |

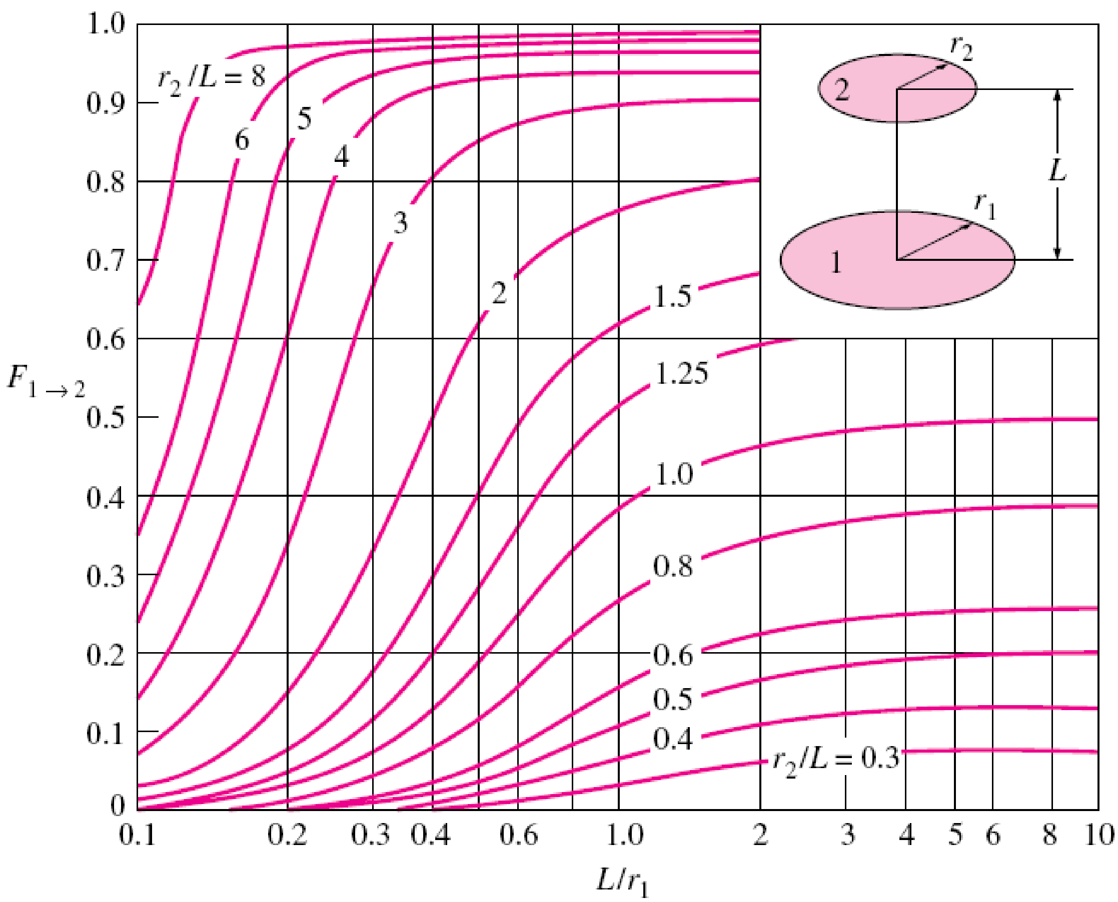
## TABLE 13–2

View factor expressions for some infinitely long (2-D) geometries

| **Geometry** | **Relation** |
|---|---|
| Parallel plates with midlines connected by perpendicular line<br> | $W_i = w_i/L$ and $W_j = w_j/L$<br>$F_{i \to j} = \dfrac{[(W_i + W_j)^2 + 4]^{1/2} - (W_j - W_i)^2 + 4]^{1/2}}{2W_i}$ |
| Inclined plates of equal width and with a common edge<br> | $F_{i \to j} = 1 - \sin \frac{1}{2}\alpha$ |
| Perpendicular plates with a common edge<br> | $F_{i \to j} = \frac{1}{2}\left\{1 + \frac{w_j}{w_i} - \left[1 + \left(\frac{w_j}{w_i}\right)^2\right]^{1/2}\right\}$ |

# Appendix 3 (Radiation)

| | |
|---|---|
| Three-sided enclosure   | $F_{i \to j} = \dfrac{w_i + w_j - w_k}{2w_i}$ |
| Infinite plane and row of cylinders   | $F_{i \to j} = 1 - \left[1 - \left(\dfrac{D}{s}\right)^2\right]^{1/2} + \dfrac{D}{s}\tan^{-1}\left(\dfrac{s^2 - D^2}{D^2}\right)^{1/2}$ |

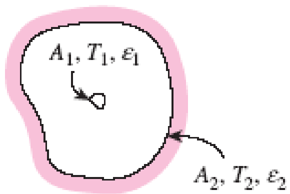


## Appendix 3 (Radiation)

**TABLE 13–3**

Radiation heat transfer relations for some familiar two-surface arrangements.

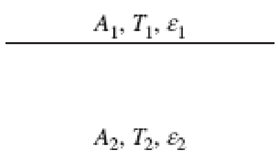
Small object in a large cavity




$$\frac{A_1}{A_2} = 0 \qquad F_{12} = 1$$

$$\dot{Q}_{12} = A_1 \sigma \varepsilon_1 (T_1^4 - T_2^4) \qquad \textbf{(13–37)}$$

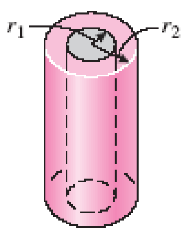
Infinitely large parallel plates




$$A_1 = A_2 = A \qquad F_{12} = 1$$

$$\dot{Q}_{12} = \frac{A\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \textbf{(13–38)}$$

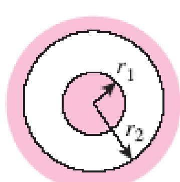
Infinitely long concentric cylinders




$$\frac{A_1}{A_2} = \frac{r_1}{r_2} \qquad F_{12} = 1$$

$$\dot{Q}_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1 - \varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)} \qquad \textbf{(13–39)}$$

Concentric spheres




$$\frac{A_1}{A_2} = \left(\frac{r_1}{r_2}\right)^2 \qquad F_{12} = 1$$

$$\dot{Q}_{12} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_2} + \frac{1 - \varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)^2} \qquad \textbf{(13–40)}$$

**Appendix 4 (Air properties)**