UNIVERSITI SAINS MALAYSIA

Second Semester Examination
Academic Session 2007/2008

April 2008

# EKC 213 – Process Heat Transfer
# *[Pemindahan Haba Proses]*

Duration : 3 hours
*[Masa : 3 jam]*

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Please check that this examination paper consists of FIVE pages of printed material and NINE page of Appendix before you begin the examination.

*[Sila pastikan bahawa kertas peperiksaan ini mengandungi LIMA muka surat yang bercetak dan SEMBILAN muka surat Lampiran sebelum anda memulakan peperiksaan ini.]*

**Instructions**: Answer any **FOUR** (4) questions.

*[**Arahan**: Jawab mana-mana **EMPAT** (4) soalan.]*

You may answer your questions either in Bahasa Malaysia or in English.

*[Anda dibenarkan menjawab soalan sama ada dalam Bahasa Malaysia atau Bahasa Inggeris.]*

Answer any FOUR questions.
*Jawab mana-mana EMPAT soalan.*

1. [a] A horizontal pipe 15 cm in diameter and 4 m long is buried in the earth with the centre at a depth of 20 cm. The pipe wall temperature is 75°C, and the heat lost by the pipe is 859.6 W. Assuming that the thermal conductivity of the earth is 0.8W/m.°C, calculate the earth surface temperature.

*Sebatang paip mendatar berdiameter 15 sm dan panjang 4 m ditanam sedalam 20 sm di bawah permukaan tanah. Dinding paip bersuhu 75°C, dan haba yang hilang daripada paip ialah 859.6 W. Anggap konduktiviti terma untuk tanah ialah 0.8W/m.°C, kirakan suhu permukaan tanah.*

[6 marks/markah]

[b] A small laboratory furnace has outside dimensions of 50 cm × 50 cm × 50 cm. The walls are 10 cm thick and made of fireclay brick (k = 0.11 W/m.K). Determine the power required for steady operation at a temperature of 600 K when the outside wall temperature is 350 K.

*Sebuah relau makmal bersaiz kecil mempunyai dimensi luar 50 sm × 50 sm × 50 sm. Dinding relau berketebalan 10 sm dan dibuat daripada bata tanah liat (k = 0.11 W/m.K). Kirakan kuasa yang diperlukan untuk operasi mantap pada suhu 600 K sekiranya dinding luar bersuhu 350 K.*

[7 marks/markah]

[c] Air at 2 atm and 200°C at the inlet is heated as it flows through a tube of diameter 2.54 cm at a velocity of 10 m/s. Calculate the:

*Udara masukan pada 2 atm dan 200°C dipanaskan semasa memasuki sebuah tiub yang berdiameter 2.54 sm pada kelajuan 10 m/s. Kirakan:*

[i] heat transfer per unit length of tube if a constant heat flux condition is maintained at the wall. The wall temperature is 20°C above the air temperature all along the length of the tube.

*perpindahan haba per panjang tiub sekiranya keadaan fluk haba malar pada dinding. Suhu dinding adalah 20°C melebihi suhu udara di sepanjang tiub.*

[7 marks/markah]

[ii] increase of the bulk temperature over a 3 m length of the tube?

*peningkatan suhu pukal sepanjang 3 m tiub?*

[5 marks/markah]

2. [a] A wall with a cross sectional area of 1 $m^2$ consists of 15 cm of concrete [k = 1.2 W/m.K], 5 cm of fiberglass insulation [k = 0.038 W/m.K], and 0.95 cm of gypsum board [k = 0.05 W/m·K]. The inside and outside convection coefficients are 11.34 and 36.69 $W/m^2 \cdot K$, respectively. The outside air temperature is -6°C, and the inside temperature is 22°C. Calculate the:

*Sebuah dinding berkeluasan 1 $m^2$ terdiri daripada konkrit [k = 1.2 W/m.K] berketebalan 15 sm, penebat kaca gentian [k = 0.038 W/m.K] berketebalan 5 sm dan papan gipsum [k = 0.05 W/m·K] berketebalan 0.95 sm. Pemalar olakan dalam dan luar masing-masing ialah 11.34 dan 36.69 $W/m^2 \cdot K$. Suhu udara di luar ialah -6°C, dan suhu di dalam ialah 22°C. Kirakan:*

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[i] overall heat-transfer coefficient for the wall
*pemalar pemindahan haba untuk dinding*

[ii] total *R* value
*nilai R keseluruhan*

[iii] heat loss
*kehilangan haba*

[iv] temperature at the interface between fiberglass and gypsum board
*suhu di antara permukaan gentian kaca dan papan gipsum*

*[12 marks/markah]*

[b] Air at 1 atm and 10°C flows across a bank of tubes 15 rows high and 5 rows deep at a velocity of 7 m/s measured at a point in the flow before the air enters the tube bank. The surfaces of the tubes are maintained at 65°C. The diameter of each tube is 2.54 cm. They are arranged in an in-line manner so that the spacing in both the normal and parallel direction to the flow is 3.81 cm. Calculate:
*Udara pada 1 atm dan 10°C mengalir melalui tiub bank yang terdiri daripada 15 baris tinggi dan 5 baris dalam pada kelajuan 7 m/s dikira pada titik aliran sebelum udara memasuki tiub bank. Suhu permukaan tiub-tiub dikekalkan pada 65°C. Diameter setiap tiub ialah 2.54 sm. Tiub-tiub ini disusun dalam aturan seragam dan jarak di antara arah normal dan selari kepada aliran ialah 3.81 sm. Kirakan:*

[i] the exit air temperature
*suhu udara keluar*

*[6 marks/markah]*

[ii] total heat transfer per unit length for the tube bank
*perpindahan haba keseluruhan per unit panjang untuk bank tiub*

*[7 marks/markah]*

3. [a] A 20 m length of mild steel steam pipe has an outside diameter of 15 cm and a wall thickness of 0.7 cm. It is insulated with a 5.3 cm-thick layer of magnesium insulation. Superheated steam at 500K flows through the pipe, and the inside heat transfer coefficient is 35 W/m$^2$·K. Heat is lost by convection to surroundings at 300K. The sum of outside convection coefficients is estimated to be 8 W/m$^2$·K. Assume steady state one-dimensional heat flow with $k_{steel}$ = 54 W/m K and $k_{magnesium}$ = 0.073 W/m·K. Find the rate of heat loss for the pipe.
*Sebuah paip keluli lembut dengan panjang 20 m, diameter luar 15 sm dan berketebalan 0.7 sm disalut dengan lapisan salutan magnesium berketebalan 5.3 sm. Stim pemanasan lampau pada 500K mengalir melalui paip tersebut. Pemalar pemindahan haba dalam ialah 35 W/m$^2$·K. Haba hilang secara perolakan ke persekitaran pada 300K. Jumlah pemalar perolakan luar ialah 8 W/m$^2$·K. Andaikan keadaan mantap dengan aliran haba pada satu dimensi serta $k_{keluli}$ = 54 W/m K dan $k_{magnesium}$ = 0.073 W/m·K. Kirakan kadar kehilangan haba untuk paip tersebut.*

*[8 marks/markah]*

[b] A fine wire having a diameter of 0.02 mm is maintained at a constant temperature of 54°C by an electric current. The wire is exposed to air at 1 atm and 0°C. Calculate the electric power necessary to maintain the wire temperature if the length is 50 cm.

*Seutas wayar halus berdiameter 0.02 mm ditetapkan suhu pada 54°C oleh arus elektrik. Wayar ini didedahkan pada udara pada 1 atm dan 0°C. Kirakan kuasa elektrik yang diperlukan untuk mengekalkan suhu wayar sekiranya panjang wayar 50 sm.*

*[8 marks/markah]*

[c] A steel plate 1 cm thick is taken from a furnace at 600°C and quenched in a bath of oil at 30°C. If the heat transfer coefficient is estimated to be 400 $W/m^2.K$, how long will it take for the plate to cool to 100°C?

Given: $k$, $\rho$, & $c_p$ for the steel as 50 W/m K, 7800 $kg/m^3$, and 450 J/kg K, respectively.

*Sebuah plat keluli berketebalan 1 sm dikeluarkan daripada relau dan dilindap-kejut di dalam takungan minyak pada 30°C. Sekiranya pemalar pemindahan haba ialah 400 $W/m^2.K$, berapakah masa yang diperlukan oleh plat untuk mencapai suhu 100°C?*

*Diberi: $k$, $\rho$, & $c_p$ untuk keluli masing-masing sebagai 50 W/m K, 7800 $kg/m^3$, dan 450 J/kg K.*

*[9 marks/markah]*

4. [a] A glass plate 1 in Figure Q.4. [a] made from a fused quartz material can transmit 80% of all incident thermal radiation of wave length between 0.2 and 0.9 μm. The plate receives radiation from a source (shown as a small oval in Figure Q.4.[a]) at a temperature of 5838°C. Assuming that the surface of plate 2 is a blackbody, calculate the radiant energy per unit area ($W/m^2$) received by plate 2 from plate 1.

*Suatu plat gelas 1 daripada Rajah S.4. [a] diperbuat daripada bahan kuartz fius yang boleh memindahkan 80% daripada keseluruhan radiasi terma pantulan gelombang di antara 0.2 dan 0.9 μm. Plat tersebut menerima daripada satu sumber (berbentuk bujur seperti di dalam Rajah S.4.[a]) radiasi pada suhu 5838°C. Andaikan permukaan plat 2 adalah badan hitam, kirakan tenaga radiasi per unit keluasan ($W/m^2$) yang diterima oleh plat 2 daripada plat 1.*

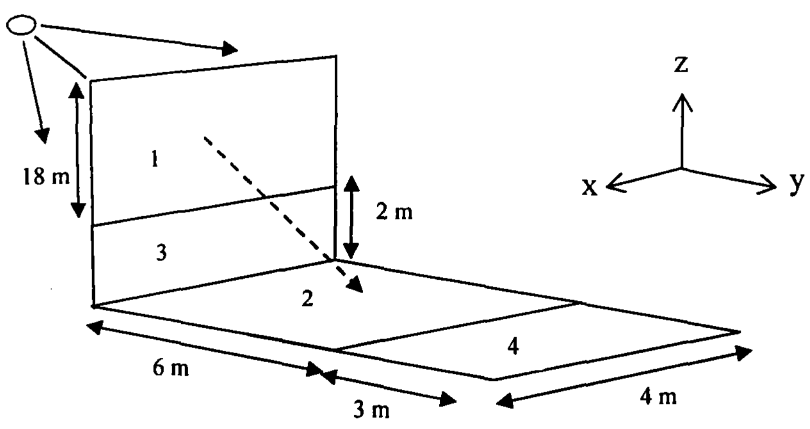


Figure Q.4. [a]
*Rajah S.4. [a]*

*[12 marks/markah]*

[b] Assuming plate 3 receives energy only from plate 2, how much energy is received by plate 3?
*Andaikan plat 3 menerima tenaga hanya daripada plat 2, berapakah tenaga yang diterima oleh plat 3?*

*[4 marks/markah]*

[c] Two parallel disks having diameters of 50 cm are separated by a distance of 12.5 cm and placed in a large room at 300K. One disk (disk 1) is at 1000K and the other (disk 2) is maintained at 500K. Calculate the heat transfer rate from each disk. Show appropriate diagram to facilitate your calculation.

(Given: $F_{1-2} = [X-(X^2-4)^{1/2}]/2$, where $X = (2R^2+1)/R^2$ and $R = d/2x$)

*Dua cakera selari bergarispusat 50 sm dipisahkan sejauh 12.5 sm dan diletakkan di sebuah bilik besar pada 300K. Satu cakera (cakera 1) adalah pada 1000K dan cakera satu lagi (cakera 2) dikekalkan pada 500K. Kirakan kadar pemindahan haba dari setiap cakera. Tunjukkan gambarajah yang bersesuaian untuk memudahkan pengiraan anda.*

*(Diberikan: $F_{1-2} = [X-(X^2-4)^{1/2}]/2$, di mana $X = (2R^2+1)/R^2$ dan $R = d/2x$)*

*[9 marks/markah]*

5. A 0.5 × 0.5 m vertical plate is maintained at 210.5K. The plate is exposed to saturated carbon dioxide at 1.0133 bar. Assuming film condensation occurs, calculate:

*Suatu 0.5 × 0.5 m plat menegak dikekalkan pada 210.5K. Plat tersebut didedahkan kepada karbon dioksida tepu pada 1.0133 bar. Andaikan kondensasi filem berlaku, kirakan:*

[a] the rate of carbon dioxide condensation
*kadar kondensasi karbon dioksida*

*[13 marks/markah]*

[b] the thickness of the carbon dioxide film at the lowest position.
*ketebalan filem karbon dioksida pada kedudukan terbawah.*

*[12 marks/markah]*

Given:
*Diberi:*
$\rho_l = 1118.281\ kg/m^3$, $\rho_g = 1.715\ kg/m^3$, $\mu = 1.72\times10^{-4}\ kg/m.s$, $h_{fg} = 343\ kJ/kg$
$C_{p,l} = 1.777\ kJ/kg.K$, $T_{sat} = 211.48\ K$, $T_s = 210.48\ K$

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## Appendix
*Lampiran*

$S_{edge}=0.54D$; $S_{corner}=0.15L$

$$Gr_x = \frac{g\beta(T_w - T_\infty)x^3}{\nu^2}$$

$$Nu_x = C(Gr_x \Pr)^m$$

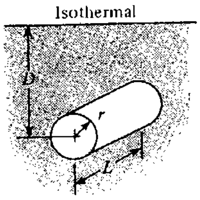
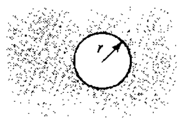
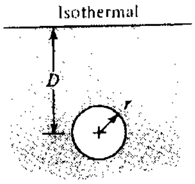
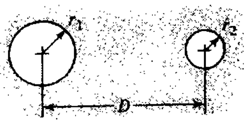
$$Bi = \frac{h\left(V/A\right)}{k}$$

$$\frac{T - T_\infty}{T_o - T_\infty} = e^{-(hA/C\rho V)\tau}$$

$$\cosh^{-1} x = \ln(x \pm \sqrt{x^2 - 1})$$

$$u_{\max} = u_\infty[S_n/(S_n - d)]$$

Conduction Shape Factors,

| *Physical system* | *Schematic* | *Shape factor* | *Restrictions* |
|---|---|---|---|
| Isothermal cylinder of radius $r$ buried in semi-infinite medium having isothermal surface |  | $\frac{2\pi L}{\cosh^{-1}(D/r)}$ | $L \gg r$ |
| | | $\frac{2\pi L}{\ln(2D/r)}$ | $L \gg r$; $D > 3r$ |
| | | $\frac{2\pi L}{\ln\frac{L}{r}\left[1 - \frac{\ln(L/2D)}{\ln(L/r)}\right]}$ | $D \gg r$; $L \gg D$ |
| Isothermal sphere of radius $r$ buried in infinite medium |  | $4\pi r$ | |
| Isothermal sphere of radius $r$ buried in semi-infinite medium having isothermal surface |  | $\frac{4\pi r}{1 - r/2D}$ | |
| Conduction between two isothermal cylinders buried in infinite medium |  | $\frac{2\pi L}{\cosh^{-1}\left(\frac{D^2 - r_1^2 - r_2^2}{2r_1r_2}\right)}$ | $L \gg r$; $L \gg D$ |

**Ratio of $h$ for $N$ rows deep to that for 10 rows deep.**

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Ratio for staggered tubes | 0.68 | 0.75 | 0.83 | 0.89 | 0.92 | 0.95 | 0.97 | 0.98 | 0.99 | 1.0 |
| Ratio for in-line tubes | 0.64 | 0.80 | 0.87 | 0.90 | 0.92 | 0.94 | 0.96 | 0.98 | 0.99 | 1.0 |

**Modified correlation of Grimson for heat transfer in tube banks of 10 rows or more**

| | $\frac{S_n}{d}$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1.25 | | 1.5 | | 2.0 | | 3.0 | |
| $\frac{S_p}{d}$ | $C$ | $n$ | $C$ | $n$ | $C$ | $n$ | $C$ | $n$ |
| **In line** | | | | | | | | |
| 1.25 | 0.386 | 0.592 | 0.305 | 0.608 | 0.111 | 0.704 | 0.0703 | 0.752 |
| 1.5 | 0.407 | 0.586 | 0.278 | 0.620 | 0.112 | 0.702 | 0.0753 | 0.744 |
| 2.0 | 0.464 | 0.570 | 0.332 | 0.602 | 0.254 | 0.632 | 0.220 | 0.648 |
| 3.0 | 0.322 | 0.601 | 0.396 | 0.584 | 0.415 | 0.581 | 0.317 | 0.608 |

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**Properties of air at atmospheric pressure†**

**The values of $\mu$, $k$, $c_p$, and Pr are not strongly pressure-dependent and may be used over a fairly wide range of pressures.**

| $T$, K | $\rho$ kg/m$^3$ | $c_p$, kJ/kg · K | $\mu \times 10^5$, kg/m · s | $\nu \times 10^6$, m$^2$/s | $k$, W/m · K | $\alpha \times 10^4$, m$^2$/s | Pr |
|---|---|---|---|---|---|---|---|
| 100 | 3.6010 | 1.0266 | 0.6924 | 1.923 | 0.009246 | 0.02501 | 0.770 |
| 150 | 2.3675 | 1.0099 | 1.0283 | 4.343 | 0.013735 | 0.05745 | 0.753 |
| 200 | 1.7684 | 1.0061 | 1.3289 | 7.490 | 0.01809 | 0.10165 | 0.739 |
| 250 | 1.4128 | 1.0053 | 1.5990 | 11.31 | 0.02227 | 0.15675 | 0.722 |
| 300 | 1.1774 | 1.0057 | 1.8462 | 15.69 | 0.02624 | 0.22160 | 0.708 |
| 350 | 0.9980 | 1.0090 | 2.075 | 20.76 | 0.03003 | 0.2983 | 0.697 |
| 400 | 0.8826 | 1.0140 | 2.286 | 25.90 | 0.03365 | 0.3760 | 0.689 |
| 450 | 0.7833 | 1.0207 | 2.484 | 31.71 | 0.03707 | 0.4222 | 0.683 |
| 500 | 0.7048 | 1.0295 | 2.671 | 37.90 | 0.04038 | 0.5564 | 0.680 |
| 550 | 0.6423 | 1.0392 | 2.848 | 44.34 | 0.04360 | 0.6532 | 0.680 |
| 600 | 0.5879 | 1.0551 | 3.018 | 51.34 | 0.04659 | 0.7512 | 0.680 |
| 650 | 0.5430 | 1.0635 | 3.177 | 58.51 | 0.04953 | 0.8578 | 0.682 |
| 700 | 0.5030 | 1.0752 | 3.332 | 66.25 | 0.05230 | 0.9672 | 0.684 |
| 750 | 0.4709 | 1.0856 | 3.481 | 73.91 | 0.05509 | 1.0774 | 0.686 |
| 800 | 0.4405 | 1.0978 | 3.625 | 82.29 | 0.05779 | 1.1951 | 0.689 |
| 850 | 0.4149 | 1.1095 | 3.765 | 90.75 | 0.06028 | 1.3097 | 0.692 |
| 900 | 0.3925 | 1.1212 | 3.899 | 99.3 | 0.06279 | 1.4271 | 0.696 |
| 950 | 0.3716 | 1.1321 | 4.023 | 108.2 | 0.06525 | 1.5510 | 0.699 |
| 1000 | 0.3524 | 1.1417 | 4.152 | 117.8 | 0.06752 | 1.6779 | 0.702 |
| 1100 | 0.3204 | 1.160 | 4.44 | 138.6 | 0.0732 | 1.969 | 0.704 |
| 1200 | 0.2947 | 1.179 | 4.69 | 159.1 | 0.0782 | 2.251 | 0.707 |
| 1300 | 0.2707 | 1.197 | 4.93 | 182.1 | 0.0837 | 2.583 | 0.705 |
| 1400 | 0.2515 | 1.214 | 5.17 | 205.5 | 0.0891 | 2.920 | 0.705 |
| 1500 | 0.2355 | 1.230 | 5.40 | 229.1 | 0.0946 | 3.262 | 0.705 |
| 1600 | 0.2211 | 1.248 | 5.63 | 254.5 | 0.100 | 3.609 | 0.705 |
| 1700 | 0.2082 | 1.267 | 5.85 | 280.5 | 0.105 | 3.977 | 0.705 |
| 1800 | 0.1970 | 1.287 | 6.07 | 308.1 | 0.111 | 4.379 | 0.704 |
| 1900 | 0.1858 | 1.309 | 6.29 | 338.5 | 0.117 | 4.811 | 0.704 |
| 2000 | 0.1762 | 1.338 | 6.50 | 369.0 | 0.124 | 5.260 | 0.702 |
| 2100 | 0.1682 | 1.372 | 6.72 | 399.6 | 0.131 | 5.715 | 0.700 |
| 2200 | 0.1602 | 1.419 | 6.93 | 432.6 | 0.139 | 6.120 | 0.707 |
| 2300 | 0.1538 | 1.482 | 7.14 | 464.0 | 0.149 | 6.540 | 0.710 |
| 2400 | 0.1458 | 1.574 | 7.35 | 504.0 | 0.161 | 7.020 | 0.718 |
| 2500 | 0.1394 | 1.688 | 7.57 | 543.5 | 0.175 | 7.441 | 0.730 |

## Summary of forced-convection relations

Subscripts: $b$ = bulk temperature, $f$ = film temperature, $\infty$ = free stream temperature, $w$ = wall temperature

| Geometry | Equation | Restrictions |
|---|---|---|
| Tube flow | $Nu_d = 0.023\, Re_d^{0.8} Pr^n$ | Fully developed turbulent flow<br>$n = 0.4$ for heating,<br>$n = 0.3$ for cooling,<br>$0.6 < Pr < 100$,<br>$2500 < Re < 1.25 \times 10^5$ |
| Tube flow | $Nu = 0.0214(Re^{0.8} - 100)Pr^{0.4}$ | $0.5 < Pr < 1.5$,<br>$10^4 < Re < 5 \times 10^6$ |
| | $Nu = 0.012(Re^{0.87} - 280)Pr^{0.4}$ | $1.5 < Pr < 500$,<br>$3000 < Re < 10^6$ |
| Tube flow | $Nu_d = 0.027\, Re_d^{0.8}\, Pr^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14}$ | Fully developed turbulent flow. |
| Tube flow, entrance region | $Nu_d = 0.036\, Re_d^{0.8}\, Pr^{1/3} \left(\frac{d}{L}\right)^{0.055}$<br>See also Figs. 6-5 and 6-6 | Turbulent flow<br>$10 < \frac{L}{d} < 400$ |
| Flow across spheres | $Nu_{df} = 0.037\, Re_{df}^{0.8}$ | $Pr \sim 0.7$ (gases),<br>$17 < Re < 70{,}000$ |
| | $NuPr^{-0.3}(\mu_w/\mu)^{0.25} = 1.2 + 0.53\, Re_d^{0.54}$ | Water and oils<br>$1 < Re < 200{,}000$<br>Properties at $T_\infty$ |
| | $Nu = 2 + (0.4\, Re_d^{1/2} + 0.06\, Re_d^{2/3}) \times Pr^{0.4}(\mu_\infty/\mu_w)^{1/4}$ | $0.7 < Pr < 380$,<br>$3.5 < Re < 80{,}000$,<br>Properties at $T_\infty$ |
| Flow across tube banks | $Nu_f = C\, Re_{f,max}^n\, Pr_f^{1/3}$<br>$C$ and $n$ from Table 6-4 | See text |

## Constants for use for isothermal surfaces

| Geometry | $Gr_f Pr_f$ | $C$ | $m$ |
|---|---|---|---|
| Vertical planes and cylinders | $10^{-1}$–$10^4$ | Use Fig. 7-7 | Use Fig. 7-7 |
| | $10^4$–$10^9$ | 0.59 | $\frac{1}{4}$ |
| | $10^9$–$10^{13}$ | 0.021 | $\frac{2}{5}$ |
| | $10^9$–$10^{13}$ | 0.10 | $\frac{1}{3}$ |
| Horizontal cylinders | 0–$10^{-5}$ | 0.4 | 0 |
| | $10^{-5}$–$10^4$ | Use Fig. 7-8 | Use Fig. 7-8 |
| | $10^4$–$10^9$ | 0.53 | $\frac{1}{4}$ |
| | $10^9$–$10^{12}$ | 0.13 | $\frac{1}{3}$ |
| | $10^{-10}$–$10^{-2}$ | 0.675 | 0.058 |
| | $10^{-2}$–$10^2$ | 1.02 | 0.148 |
| | $10^2$–$10^4$ | 0.850 | 0.188 |
| | $10^4$–$10^7$ | 0.480 | $\frac{1}{4}$ |
| | $10^7$–$10^{12}$ | 0.125 | $\frac{1}{3}$ |
| Upper surface of heated plates or lower surface of cooled plates | $2 \times 10^4$–$8 \times 10^6$ | 0.54 | $\frac{1}{4}$ |
| Upper surface of heated plates or lower surface of cooled plates | $8 \times 10^6$–$10^{11}$ | 0.15 | $\frac{1}{3}$ |
| Lower surface of heated plates or upper surface of cooled plates | $10^5$–$10^{11}$ | 0.27 | $\frac{1}{4}$ |
| Vertical cylinder, height = diameter Characteristic length= diameter | $10^4$–$10^6$ | 0.775 | 0.21 |

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System of unit conversion

| Quantity | Equivalent unit |
|---|---|
| Mass | 1 kg = 1000 g = 0.001 metric ton = 2.20462 $Ib_m$ = 35.27392 ounces<br>1 $Ib_m$ = 16 ounces = $5\times10^{-4}$ tons = 453.593 g = 0.453593 kg |
| Length | 1 m = 100 cm = 1000 mm = $10^6$ μm = $10^{10}$ angstrom = 39.37 in<br>= 3.2808 ft = 1.0936 yards = 0.0006214 mile. |
| Volume | 1 $m^3$ = 1000 L = $10^6$ $cm^3$ = $10^6$ ml<br>= 35.3145 $ft^3$ = 264.17 gal<br>1 $ft^3$ = 1728 $in^3$ = 7.4805 gal = 0.028317 $m^3$ = 28.317 L = 28317 $cm^3$ |
| Force | 1 N = 1 kg.m.$s^{-2}$ = $10^5$ dyne = $10^5$ g.cm.$s^{-2}$ = 0.22481 $Ib_f$<br>1 $Ib_f$ = 32.174 $Ib_m$ ft.$s^{-2}$ = 4.4482 N |
| Pressure | 1 atm = $1.01325\times10^5$ N/$m^2$ (Pa) = $1.01325\times10^5$ kg/(m.$s^2$) = 760 torr<br>= 760 mmHg = 14.696 psi = 1.01325 bar |
| Energy | 1 J = 1 N.m = $10^7$ dyne.cm = $2.778\times10^{-7}$ kW.h = 0.23901 kal<br>= 0.7376 ft-$Ib_f$ = $9.486\times10^{-4}$ Btu |
| Power | 1 W = 1 J/s = 0.23901 cal/s = 0.7376 ft-$Ib_f$/s = $9.486\times10^{-4}$ Btu/s<br>= $1.341\times10^{-3}$ hp |

| Gas constant | Other constants |
|---|---|
| 8.314 $m^3$.Pa/mol.K<br>0.08314 liter. bar/mol.K<br>0.08206 liter.atm/mol.K<br>62.36 liter.mmHg/mol.K<br>0.7302 $ft^3$ atm/Ib-mole.°R<br>10.73 $ft^3$.psia/Ib-mole.°R<br>82.06 $cm^3$.atm/mol.K<br>8.314 J/mol.K<br>1.987 cal/mol.K<br>1.987 Btu/Ib-mole.°R | h = $6.625\times10^{-34}$ Js (Plank's constant)<br>σ = $5.669\times10^{-8}$ (Stefan-Boltzman constant) |

Properties of saturated steam

| $T$ (°C) | $P$ (bar) | $V$ ($m^3$/kg) | | $U$ (KJ/kg) | | $H$ (KJ/kg) | | |
|---|---|---|---|---|---|---|---|---|
| | | $V_f$ | $V_g$ | $U_f$ | $U_g$ | $H_f$ | $H_{fg}$ | $H_g$ |
| 10 | 0.01227 | 0.001000 | 106.4 | 42.0 | 2389.3 | 42.0 | 2477.9 | 2519.9 |
| 20 | 0.0234 | 0.001002 | 57.8 | 83.9 | 2403.0 | 83.9 | 2454.3 | 2538.2 |
| 30 | 0.0424 | 0.001004 | 32.9 | 125.7 | 2416.7 | 125.7 | 2430.7 | 2556.4 |
| 40 | 0.0738 | 0.001008 | 19.55 | 167.4 | 2430.2 | 167.5 | 2406.9 | 2574.4 |
| 50 | 0.1234 | 0.001012 | 12.05 | 209.2 | 2443.6 | 209.3 | 2382.9 | 2592.2 |
| 60 | 0.1992 | 0.001017 | 7.678 | 251.1 | 2456 | 251.1 | 2358 | 2609 |
| 70 | 0.3117 | 0.001023 | 5.045 | 293.0 | 2469 | 293.0 | 2333 | 2626 |
| 80 | 0.4736 | 0.001029 | 3.408 | 334.8 | 2482 | 334.9 | 2308 | 2643 |
| 90 | 0.7011 | 0.001036 | 2.361 | 376.9 | 2493 | 377.0 | 2282 | 2659 |
| 100 | 1.0131 | 0.001044 | 1.673 | 419.0 | 2507 | 419.0 | 2255 | 2674 |

$V$ = specific volume  $U$ = specific internal energy  $H$ = specific enthalpy

**Radiation function**

| $\lambda T$ $\mu mK$ | $E_{b\lambda}/T^5$ $\frac{W}{m^2K^5\mu m\times10^{11}}$ | $\frac{E_{b0-\lambda T}}{\sigma T^4}$ | $\lambda T$ $\mu mK$ | $E_{b\lambda}/T^5$ $\frac{W}{m^2K^5\mu m\times10^{11}}$ | $\frac{E_{b0-\lambda T}}{\sigma T^4}$ |
|---|---|---|---|---|---|
| 1000 | 0.02110 | 0.00032 | 5100 | 0.68628 | 0.64606 |
| 1100 | 0.04846 | 0.00091 | 5200 | 0.65983 | 0.65794 |
| 1200 | 0.09329 | 0.00213 | 5300 | 0.63432 | 0.66935 |
| 1300 | 0.15724 | 0.00432 | 5400 | 0.60974 | 0.68033 |
| 1400 | 0.23932 | 0.00779 | 5500 | 0.58608 | 0.69087 |
| 1500 | 0.33631 | 0.01285 | 5600 | 0.56332 | 0.70101 |
| 1600 | 0.44359 | 0.01972 | 5700 | 0.54146 | 0.71076 |
| 1700 | 0.55603 | 0.02853 | 5800 | 0.52046 | 0.72012 |
| 1800 | 0.66872 | 0.03934 | 5900 | 0.50030 | 0.72913 |
| 1900 | 0.77736 | 0.05210 | 6000 | 0.48096 | 0.73778 |
| 2000 | 0.87858 | 0.06672 | 6100 | 0.46242 | 0.74610 |
| 2100 | 0.96994 | 0.08305 | 6200 | 0.44464 | 0.75410 |
| 2200 | 1.04990 | 0.10088 | 6300 | 0.42760 | 0.76180 |
| 2300 | 1.11768 | 0.12002 | 6400 | 0.41128 | 0.76920 |
| 2400 | 1.17314 | 0.14025 | 6500 | 0.39564 | 0.77631 |
| 2500 | 1.21659 | 0.16135 | 6600 | 0.38066 | 0.78316 |
| 2600 | 1.24868 | 0.18311 | 6700 | 0.36631 | 0.78975 |
| 2700 | 1.27029 | 0.20535 | 6800 | 0.35256 | 0.79609 |
| 2800 | 1.28242 | 0.22788 | 6900 | 0.33940 | 0.80219 |
| 2900 | 1.28612 | 0.25055 | 7000 | 0.32679 | 0.80807 |
| 3000 | 1.28245 | 0.27322 | 7100 | 0.31471 | 0.81373 |
| 3100 | 1.27242 | 0.29576 | 7200 | 0.30315 | 0.81918 |
| 3200 | 1.25702 | 0.31809 | 7300 | 0.29207 | 0.82443 |
| 3300 | 1.23711 | 0.34009 | 7400 | 0.28146 | 0.82949 |
| 3400 | 1.21352 | 0.36172 | 7500 | 0.27129 | 0.83436 |
| 3500 | 1.18695 | 0.38290 | 7600 | 0.26155 | 0.83906 |
| 3600 | 1.15806 | 0.40359 | 7700 | 0.25221 | 0.84359 |
| 3700 | 1.12739 | 0.42375 | 7800 | 0.24326 | 0.84796 |
| 3800 | 1.09544 | 0.44336 | 7900 | 0.23468 | 0.85218 |
| 3900 | 1.06261 | 0.46240 | 8000 | 0.22646 | 0.85625 |
| 4000 | 1.02927 | 0.48085 | 8100 | 0.21857 | 0.86017 |
| 4100 | 0.99571 | 0.49872 | 8200 | 0.21101 | 0.86396 |
| 4200 | 0.96220 | 0.51599 | 8300 | 0.20375 | 0.86762 |
| 4300 | 0.92892 | 0.53267 | 8400 | 0.19679 | 0.87115 |
| 4400 | 0.89607 | 0.54877 | 8500 | 0.19011 | 0.87456 |
| 4500 | 0.86376 | 0.56429 | 8600 | 0.18370 | 0.87786 |
| 4600 | 0.83212 | 0.57925 | 8700 | 0.17755 | 0.88105 |
| 4700 | 0.80124 | 0.59366 | 8800 | 0.17164 | 0.88413 |
| 4800 | 0.77117 | 0.60753 | 8900 | 0.16596 | 0.88711 |
| 4900 | 0.74197 | 0.62088 | 9000 | 0.16051 | 0.88999 |
| 5000 | 0.71366 | 0.63372 | 9100 | 0.15527 | 0.89277 |

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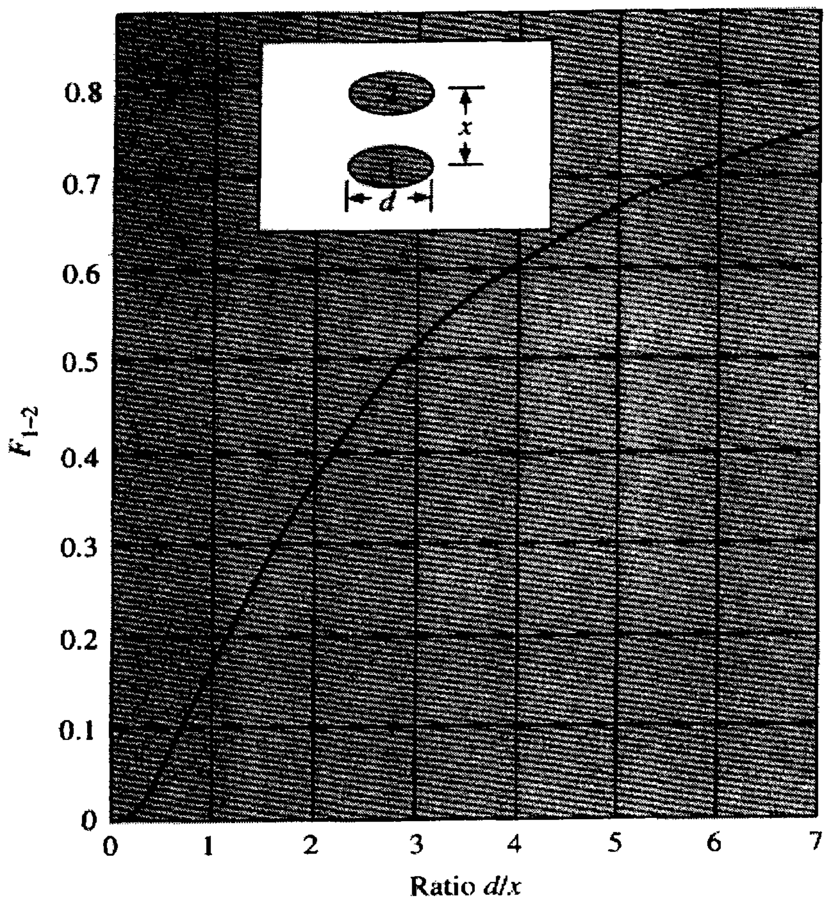
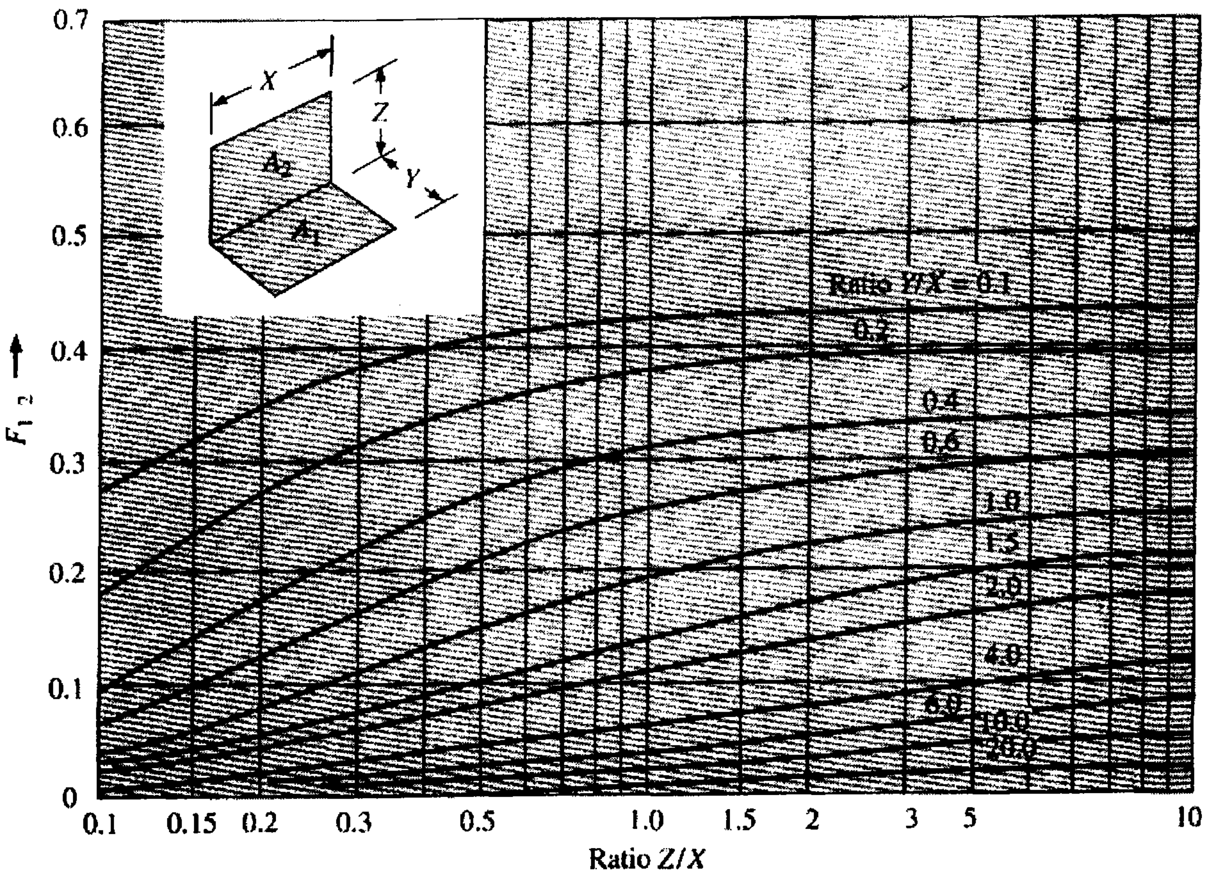
**Radiation function (continue)**

| $\lambda T$ $\mu mK$ | $E_{b\lambda}/T^5$ $\frac{W}{m^2K^5\mu m\times10^{11}}$ | $\frac{E_{b0-\lambda T}}{\sigma T^4}$ | $\lambda T$ $\mu mK$ | $E_{b\lambda}/T^5$ $\frac{W}{m^2K^5\mu m\times10^{11}}$ | $\frac{E_{b0-\lambda T}}{\sigma T^4}$ |
|---|---|---|---|---|---|
| 9200 | 0.15024 | 0.89547 | 16600 | 0.02152 | 0.97620 |
| 9300 | 0.14540 | 0.89807 | 16800 | 0.02063 | 0.97694 |
| 9400 | 0.14075 | 0.90060 | 17000 | 0.01979 | 0.97765 |
| 9500 | 0.13627 | 0.90304 | 17200 | 0.01899 | 0.97834 |
| 9600 | 0.13197 | 0.90541 | 17400 | 0.01823 | 0.97899 |
| 9700 | 0.12783 | 0.90770 | 17600 | 0.01751 | 0.97962 |
| 9800 | 0.12384 | 0.90992 | 17800 | 0.01682 | 0.98023 |
| 9900 | 0.12001 | 0.91207 | 18000 | 0.01617 | 0.98081 |
| 10000 | 0.11632 | 0.91415 | 18200 | 0.01555 | 0.98137 |
| 10200 | 0.10934 | 0.91813 | 18400 | 0.01496 | 0.98191 |
| 10400 | 0.10287 | 0.92188 | 18600 | 0.01439 | 0.98243 |
| 10600 | 0.09685 | 0.92540 | 18800 | 0.01385 | 0.98293 |
| 10800 | 0.09126 | 0.92872 | 19000 | 0.01334 | 0.98340 |
| 11000 | 0.08606 | 0.93184 | 19200 | 0.01285 | 0.98387 |
| 11200 | 0.08121 | 0.93479 | 19400 | 0.01238 | 0.98431 |
| 11400 | 0.07670 | 0.93758 | 19600 | 0.01193 | 0.98474 |
| 11600 | 0.07249 | 0.94021 | 19800 | 0.01151 | 0.98515 |
| 11800 | 0.06856 | 0.94270 | 20000 | 0.01110 | 0.98555 |
| 12000 | 0.06488 | 0.94505 | 21000 | 0.00931 | 0.98735 |
| 12200 | 0.06145 | 0.94728 | 22000 | 0.00786 | 0.98886 |
| 12400 | 0.05823 | 0.94939 | 23000 | 0.00669 | 0.99014 |
| 12600 | 0.05522 | 0.95139 | 24000 | 0.00572 | 0.99123 |
| 12800 | 0.05240 | 0.95329 | 25000 | 0.00492 | 0.99217 |
| 13000 | 0.04976 | 0.95509 | 26000 | 0.00426 | 0.99297 |
| 13200 | 0.04728 | 0.95680 | 27000 | 0.00370 | 0.99367 |
| 13400 | 0.04494 | 0.95843 | 28000 | 0.00324 | 0.99429 |
| 13600 | 0.04275 | 0.95998 | 29000 | 0.00284 | 0.99482 |
| 13800 | 0.04069 | 0.96145 | 30000 | 0.00250 | 0.99529 |
| 14000 | 0.03875 | 0.96285 | 31000 | 0.00221 | 0.99571 |
| 14200 | 0.03693 | 0.96418 | 32000 | 0.00196 | 0.99607 |
| 14400 | 0.03520 | 0.96546 | 33000 | 0.00175 | 0.99640 |
| 14600 | 0.03358 | 0.96667 | 34000 | 0.00156 | 0.99669 |
| 14800 | 0.03205 | 0.96783 | 35000 | 0.00140 | 0.99695 |
| 15000 | 0.03060 | 0.96893 | 36000 | 0.00126 | 0.99719 |
| 15200 | 0.02923 | 0.96999 | 37000 | 0.00113 | 0.99740 |
| 15400 | 0.02794 | 0.97100 | 38000 | 0.00103 | 0.99759 |
| 15600 | 0.02672 | 0.97196 | 39000 | 0.00093 | 0.99776 |
| 15800 | 0.02556 | 0.97288 | 40000 | 0.00084 | 0.99792 |
| 16000 | 0.02447 | 0.97377 | 41000 | 0.00077 | 0.99806 |
| 16200 | 0.02343 | 0.97461 | 42000 | 0.00070 | 0.99819 |
| 16400 | 0.02245 | 0.97542 | 43000 | 0.00064 | 0.99831 |

...7/-




Radiation shape factor for radiation between parallel disks.




Radiation shape factor for radiation between perpendicular rectangles with a common edge.

$$E_{b\lambda} = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}$$

$$\lambda_{max} T = C_3$$

$$\frac{\bar{h}\left(\nu^2/g\right)^{1/3}}{k_l} = 1.47\,\mathrm{Re}^{-1/3}$$

$$\mathrm{Re}_\delta = \frac{4\dot{m}}{\mu_l b}$$

$$\delta(x) = \left[\frac{4k_l \mu_l (T_{sat} - T_s)x}{g\rho_l(\rho_l - \rho_v)h_{fg}}\right]^{1/4}$$

$$\bar{h} = 0.943\left[\frac{\rho_l(\rho_l - \rho_v)gh_{fg}k_l^3}{\mu_l(T_{sat} - T_s)L}\right]^{1/4}$$

$$\Delta \mathrm{p} = \frac{\nu_1 G^2}{2g_c}\left[(1+\sigma^2)\left(\frac{\nu_2}{\nu_1} - 1\right) + f\frac{A}{A_c}\frac{\nu_m}{\nu_1}\right]$$

$$G = \frac{\dot{m}}{A_c} = \frac{\rho u_\infty A}{A_c}$$

$$Re = \frac{D_h G}{\mu}$$

$$\sigma = \frac{A_c}{A}$$

$$\mathrm{St} = \frac{h}{Gc_p}$$

$$\frac{\bar{h}\left(\nu^2/g\right)^{1/3}}{k_l} = \frac{\mathrm{Re}}{1.08\,\mathrm{Re}^{1.22} - 5.2}; \qquad 30 \le \mathrm{Re}_\delta \le 1800$$

$$\mathrm{Gr} = \frac{\rho^2 g\beta(\Delta T)d^3}{\mu^2}$$

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$$

$$\bar{h} = c\left[\frac{\rho_l(\rho_l - \rho_v)gh_{fg}'k_l^3}{N\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$, where $c$=0.726 (on tube), $c$=0.555 (in tube)

$$h_{fg}' = h_{fg} + 0.375c_{p,l}(T_{sat} - T_s)$$

...9/-

| |
|---|
| $q = \mu_l h_{fg} \left[ \frac{g(\rho_l - \rho_v)}{\sigma'} \right]^{1/2} \left( \frac{c_{p,l} \Delta T_x}{C_{sf} h_{fg} \Pr_l^s} \right)^3$ |
| $\frac{\bar{h}(v^2/g)^{1/3}}{k_l} = \frac{\text{Re}}{8750 + 58\Pr^{-0.5}(\text{Re}^{0.75} - 253)}$; $\text{Re}_\delta \geq 1800$ |
| $h^{4/3} = h_{conv}^{4/3} + h_{rad} h^{1/3}$ <br> $h_{conv} = \frac{C k_v}{D} \left[ \frac{g(\rho_l - \rho_v) h_{fg} D^3}{\nu_v k_v (T_s - T_{sat})} \right]^{1/4}$ <br> $C = 0.62$ (horizontal cylinder), 0.67 (sphere) |
| $h_{rad} = \frac{\varepsilon \sigma (T_s^4 - T_{sat}^4)}{(T_s - T_{sat})}$ |
| $\frac{q}{A} = 2.253(\Delta T_x)^{3.96}$ W/m² ; $2 < p < 6$ atm <br> $\frac{q}{A} = 283.2 p^{4/3} (\Delta T_x)^3$ W/m² ; $8 < p < 14$ atm |
| $h = 2.54(\Delta T_x)^3 e^{p/1.551}$ |
| $\frac{q}{A} = 2.253(\Delta T_x)^{3.96}$ |

**Table 1:** Radiation function (continue)

| $\lambda T$ $\mu$mK | $E_{b\lambda}/T^5$ $\frac{W}{m^2 K^5 \mu m \times 10^{11}}$ | $\frac{E_{b0-\lambda T}}{\sigma T^4}$ |
|---|---|---|
| 44000 | 0.00059 | 0.99842 |
| 45000 | 0.00054 | 0.99851 |
| 46000 | 0.00049 | 0.99861 |
| 47000 | 0.00046 | 0.99869 |
| 48000 | 0.00042 | 0.99877 |
| 49000 | 0.00039 | 0.99884 |
| 50000 | 0.00036 | 0.99890 |