

Chapter 12

12-1 Given: $d_{\max} = 25$ mm, $b_{\min} = 25.03$ mm, $l/d = 1/2$, $W = 1.2$ kN, $\mu = 55$ mPa·s, and $N = 1100$ rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{25.03 - 25}{2} = 0.015 \text{ mm}$$

$$r \doteq 25/2 = 12.5 \text{ mm}$$

$$r/c = 12.5/0.015 = 833.3$$

$$N = 1100/60 = 18.33 \text{ rev/s}$$

$$P = W/(ld) = 1200/[12.5(25)] = 3.84 \text{ N/mm}^2 = 3.84 \text{ MPa}$$

Eq. (12-7):
$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 833.3^2 \left[\frac{55(10^{-3})18.33}{3.84(10^6)} \right] = 0.182$$

Fig. 12-16: $h_0/c = 0.3 \Rightarrow h_0 = 0.3(0.015) = 0.0045 \text{ mm} \quad \text{Ans.}$

Fig. 12-18: $f r/c = 5.4 \Rightarrow f = 5.4/833.3 = 0.00648$

$$T = f W r = 0.00648(1200)12.5(10^{-3}) = 0.0972 \text{ N}\cdot\text{m}$$

$$H_{\text{loss}} = 2\pi T N = 2\pi(0.0972)18.33 = 11.2 \text{ W} \quad \text{Ans.}$$

Fig. 12-19: $Q/(rcNI) = 5.1 \Rightarrow Q = 5.1(12.5)0.015(18.33)12.5 = 219 \text{ mm}^3/\text{s}$

Fig. 12-20: $Q_s/Q = 0.81 \Rightarrow Q_s = 0.81(219) = 177 \text{ mm}^3/\text{s} \quad \text{Ans.}$

12-2 Given: $d_{\max} = 32$ mm, $b_{\min} = 32.05$ mm, $l = 64$ mm, $W = 1.75$ kN, $\mu = 55$ mPa·s, and $N = 900$ rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{32.05 - 32}{2} = 0.025 \text{ mm}$$

$$r \doteq 32/2 = 16 \text{ mm}$$

$$r/c = 16/0.025 = 640$$

$$N = 900/60 = 15 \text{ rev/s}$$

$$P = W/(ld) = 1750/[32(64)] = 0.854 \text{ MPa}$$

$$l/d = 64/32 = 2$$

$$\text{Eq. (12-7): } S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 640^2 \left[\frac{55(10^{-3})15}{0.854} \right] = 0.797$$

Eq. (12-16), Figs. 12-16, 12-19, and 12-21

	l/d	y_∞	y_1	$y_{1/2}$	$y_{1/4}$	$y_{1/d}$
h_0/c	2	0.98	0.83	0.61	0.36	0.92
P/p_{\max}	2	0.84	0.54	0.45	0.31	0.65
$Q/rcNl$	2	3.1	3.45	4.2	5.08	3.20

$$h_0 = 0.92 c = 0.92(0.025) = 0.023 \text{ mm} \quad \text{Ans.}$$

$$p_{\max} = P / 0.65 = 0.854/0.65 = 1.31 \text{ MPa} \quad \text{Ans.}$$

$$Q = 3.20 rcNl = 3.20(16)0.025(15)64 = 1.23 (10^3) \text{ mm}^3/\text{s} \quad \text{Ans.}$$

12-3 Given: $d_{\max} = 3.000$ in, $b_{\min} = 3.005$ in, $l = 1.5$ in, $W = 800$ lbf, $N = 600$ rev/min, and SAE 10 and SAE 40 at 150°F.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.005 - 3.000}{2} = 0.0025 \text{ in}$$

$$r = 3.000 / 2 = 1.500 \text{ in}$$

$$l/d = 1.5 / 3 = 0.5$$

$$r/c = 1.5 / 0.0025 = 600$$

$$N = 600 / 60 = 10 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{800}{1.5(3)} = 177.78 \text{ psi}$$

Fig. 12-12: SAE 10 at 150°F, $\mu' = 1.75 \mu\text{reyn}$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 600^2 \left[\frac{1.75(10^{-6})(10)}{177.78} \right] = 0.0354$$

Figs. 12-16 and 12-21: $h_0/c = 0.11$ and $P/p_{\max} = 0.21$
 $h_0 = 0.11(0.0025) = 0.000275 \text{ in} \quad \text{Ans.}$
 $p_{\max} = 177.78 / 0.21 = 847 \text{ psi} \quad \text{Ans.}$

Fig. 12-12: SAE 40 at 150°F, $\mu' = 4.5 \mu\text{reyn}$

$$S = 0.0354 \left(\frac{4.5}{1.75} \right) = 0.0910$$

$$h_0 / c = 0.19, \quad P / p_{\max} = 0.275$$

$$h_0 = 0.19(0.0025) = 0.000475 \text{ in} \quad \text{Ans.}$$

$$p_{\max} = 177.78 / 0.275 = 646 \text{ psi} \quad \text{Ans.}$$

12-4 Given: $d_{\max} = 3.250 \text{ in}$, $b_{\min} = 3.256 \text{ in}$, $l = 3.25 \text{ in}$, $W = 800 \text{ lbf}$, and $N = 1000 \text{ rev/min}$.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.256 - 3.250}{2} = 0.003$$

$$r \doteq 3.250 / 2 = 1.625 \text{ in}$$

$$l / d = 3 / 3.250 = 0.923$$

$$r / c = 1.625 / 0.003 = 542$$

$$N = 1000 / 60 = 16.67 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{800}{3(3.25)} = 82.05 \text{ psi}$$

Fig. 12-14: SAE 20W at 150°F, $\mu' = 2.85 \mu \text{ reyn}$

$$S = \left(\frac{r}{c} \right)^2 \frac{\mu N}{P} = 542^2 \left[\frac{2.85(10^{-6})(16.67)}{82.05} \right] = 0.1701$$

From Eq. (12-16), and Figs. 12-16 and 12-21:

	l/d	y_{∞}	y_1	$y_{1/2}$	$y_{1/4}$	$y_{1/d}$
h_0/c	0.923	0.85	0.48	0.28	0.15	0.46
P/p_{\max}	0.923	0.83	0.45	0.32	0.22	0.43

$$h_0 = 0.46c = 0.46(0.003) = 0.00138 \text{ in} \quad \text{Ans.}$$

$$p_{\max} = \frac{P}{0.43} = \frac{82.05}{0.43} = 191 \text{ psi} \quad \text{Ans.}$$

Fig. 12-14: SAE 20W-40 at 150°F, $\mu' = 4.4 \mu \text{ reyn}$

$$S = 542^2 \frac{4.4(10^{-6})(16.67)}{82.05} = 0.263$$

From Eq. (12-16), and Figs. 12-16 and 12-21:

	l/d	y_{∞}	y_1	$y_{1/2}$	$y_{1/4}$	$y_{1/d}$
h_0/c	0.923	0.91	0.6	0.38	0.2	0.58
P/p_{\max}	0.923	0.83	0.48	0.35	0.24	0.46

$$h_0 = 0.58c = 0.58(0.003) = 0.00174 \text{ in} \quad \text{Ans.}$$

$$p_{\max} = \frac{8205}{0.46} = \frac{82.05}{0.46} = 178 \text{ psi} \quad \text{Ans.}$$

12-5 Given: $d_{\max} = 2.000 \text{ in}$, $b_{\min} = 2.0024 \text{ in}$, $l = 1 \text{ in}$, $W = 600 \text{ lbf}$, $N = 800 \text{ rev/min}$, and SAE 20 at 130°F .

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{2.0024 - 2}{2} = 0.0012 \text{ in}$$

$$r \doteq \frac{d}{2} = \frac{2}{2} = 1 \text{ in}, \quad l/d = 1/2 = 0.50$$

$$r/c = 1/0.0012 = 833$$

$$N = 800/60 = 13.33 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{600}{2(1)} = 300 \text{ psi}$$

Fig. 12-12: SAE 20 at 130°F , $\mu' = 3.75 \mu\text{reyn}$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 833^2 \left[\frac{3.75(10^{-6})(13.3)}{300} \right] = 0.115$$

From Figs. 12-16, 12-18 and 12-19:

$$h_0/c = 0.23, \quad rf/c = 3.8, \quad Q/(rcNl) = 5.3$$

$$h_0 = 0.23(0.0012) = 0.000276 \text{ in} \quad \text{Ans.}$$

$$f = \frac{3.8}{833} = 0.00456$$

The power loss due to friction is

$$H = \frac{2\pi f WrN}{778(12)} = \frac{2\pi(0.00456)(600)(1)(13.33)}{778(12)}$$

$$= 0.0245 \text{ Btu/s} \quad \text{Ans.}$$

$$Q = 5.3rcNl$$

$$= 5.3(1)(0.0012)(13.33)(1)$$

$$= 0.0848 \text{ in}^3/\text{s} \quad \text{Ans.}$$

12-6 Given: $d_{\max} = 25 \text{ mm}$, $b_{\min} = 25.04 \text{ mm}$, $l/d = 1$, $W = 1.25 \text{ kN}$, $\mu = 50 \text{ mPa}\cdot\text{s}$, and $N = 1200 \text{ rev/min}$.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{25.04 - 25}{2} = 0.02 \text{ mm}$$

$$r = d / 2 = 25 / 2 = 12.5 \text{ mm}, \quad l / d = 1$$

$$r / c = 12.5 / 0.02 = 625$$

$$N = 1200 / 60 = 20 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{1250}{25^2} = 2 \text{ MPa}$$

$$\text{For } \mu = 50 \text{ MPa} \cdot \text{s}, \quad S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 625^2 \left[\frac{50(10^{-3})(20)}{2(10^6)} \right] = 0.195$$

From Figs. 12-16, 12-18 and 12-20:

$$h_0 / c = 0.52, \quad f r / c = 4.5, \quad Q_s / Q = 0.57$$

$$h_0 = 0.52(0.02) = 0.0104 \text{ mm} \quad \text{Ans.}$$

$$f = \frac{4.5}{625} = 0.0072$$

$$T = f W r = 0.0072(1.25)(12.5) = 0.1125 \text{ N} \cdot \text{m}$$

The power loss due to friction is

$$H = 2\pi T N = 2\pi (0.1125)(20) = 14.14 \text{ W} \quad \text{Ans.}$$

$$Q_s = 0.57Q \quad \text{The side flow is 57\% of } Q \quad \text{Ans.}$$

12-7 Given: $d_{\max} = 1.25$ in, $b_{\min} = 1.252$ in, $l = 2$ in, $W = 620$ lbf, $\mu' = 8.5 \mu \text{ reyn}$, and $N = 1120$ rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{1.252 - 1.25}{2} = 0.001 \text{ in}$$

$$r = d / 2 = 1.25 / 2 = 0.625 \text{ in}$$

$$r / c = 0.625 / 0.001 = 625$$

$$N = 1120 / 60 = 18.67 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{620}{1.25(2)} = 248 \text{ psi}$$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 625^2 \left[\frac{8.5(10^{-6})(18.67)}{248} \right] = 0.250$$

$$l / d = 2 / 1.25 = 1.6$$

From Eq. (12-16), and Figs. 12-16, 12-18, and 12-19

	l/d	y_∞	y_1	$y_{1/2}$	$y_{1/4}$	$y_{1/d}$
h_0/c	1.6	0.9	0.58	0.36	0.185	0.69
fr/c	1.6	4.5	5.3	6.5	8	4.92
$Q/rcNl$	1.6	3	3.98	4.97	5.6	3.59

$$h_0 = 0.69 c = 0.69(0.001) = 0.00069 \text{ in} \quad \text{Ans.}$$

$$f = 4.92/(r/c) = 4.92/625 = 0.00787 \quad \text{Ans.}$$

$$Q = 1.6 rcNl = 1.6(0.625) 0.001(18.57)^2 = 0.0833 \text{ in}^3/\text{s} \quad \text{Ans.}$$

12-8 Given: $d_{\max} = 75.00 \text{ mm}$, $b_{\min} = 75.10 \text{ mm}$, $l = 36 \text{ mm}$, $W = 2 \text{ kN}$, $N = 720 \text{ rev/min}$, and SAE 20 and SAE 40 at 60°C .

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{75.10 - 75}{2} = 0.05 \text{ mm}$$

$$l/d = 36/75 = 0.48 \approx 0.5 \quad (\text{close enough})$$

$$r = d/2 = 75/2 = 37.5 \text{ mm}$$

$$r/c = 37.5/0.05 = 750$$

$$N = 720/60 = 12 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{2000}{75(36)} = 0.741 \text{ MPa}$$

Fig. 12-13: SAE 20 at 60°C , $\mu = 18.5 \text{ MPa} \cdot \text{s}$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 750^2 \left[\frac{18.5(10^{-3})(12)}{0.741(10^6)} \right] = 0.169$$

From Figures 12-16, 12-18 and 12-21:

$$h_0/c = 0.29, \quad fr/c = 5.1, \quad P/p_{\max} = 0.315$$

$$h_0 = 0.29(0.05) = 0.0145 \text{ mm} \quad \text{Ans.}$$

$$f = 5.1/750 = 0.0068$$

$$T = fWr = 0.0068(2)(37.5) = 0.51 \text{ N} \cdot \text{m}$$

The heat loss rate equals the rate of work on the film

$$H_{\text{loss}} = 2\pi TN = 2\pi(0.51)(12) = 38.5 \text{ W} \quad \text{Ans.}$$

$$p_{\max} = 0.741/0.315 = 2.35 \text{ MPa} \quad \text{Ans.}$$

Fig. 12-13: SAE 40 at 60°C , $\mu = 37 \text{ MPa} \cdot \text{s}$

$$S = 0.169(37)/18.5 = 0.338$$

From Figures 12-16, 12-18 and 12-21:

$$\begin{aligned} h_0 / c &= 0.42, \quad f r / c = 8.5, \quad P / p_{\max} = 0.38 \\ h_0 &= 0.42(0.05) = 0.021 \text{ mm} \quad \text{Ans.} \\ f &= 8.5 / 750 = 0.0113 \\ T &= f W r = 0.0113(2)(37.5) = 0.85 \text{ N} \cdot \text{m} \\ H_{\text{loss}} &= 2\pi T N = 2\pi(0.85)(12) = 64 \text{ W} \quad \text{Ans.} \\ p_{\max} &= 0.741 / 0.38 = 1.95 \text{ MPa} \quad \text{Ans.} \end{aligned}$$

12-9 Given: $d_{\max} = 56.00 \text{ mm}$, $b_{\min} = 56.05 \text{ mm}$, $l = 28 \text{ mm}$, $W = 2.4 \text{ kN}$, $N = 900 \text{ rev/min}$, and SAE 40 at 65°C .

$$\begin{aligned} c_{\min} &= \frac{b_{\min} - d_{\max}}{2} = \frac{56.05 - 56}{2} = 0.025 \text{ mm} \\ r &= d / 2 = 56 / 2 = 28 \text{ mm} \\ r / c &= 28 / 0.025 = 1120 \\ l / d &= 28 / 56 = 0.5, \quad N = 900 / 60 = 15 \text{ rev/s} \\ P &= \frac{2400}{28(56)} = 1.53 \text{ MPa} \end{aligned}$$

Fig. 12-13: SAE 40 at 65°C , $\mu = 30 \text{ MPa} \cdot \text{s}$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 1120^2 \left[\frac{30(10^{-3})(15)}{1.53(10^6)} \right] = 0.369$$

From Figures 12-16, 12-18, 12-19 and 12-20:

$$\begin{aligned} h_0 / c &= 0.44, \quad f r / c = 8.5, \quad Q_s / Q = 0.71, \quad Q / (rcNl) = 4.85 \\ h_0 &= 0.44(0.025) = 0.011 \text{ mm} \quad \text{Ans.} \\ f &= 8.5 / 1000 = 0.00759 \\ T &= f W r = 0.00759(2.4)(28) = 0.51 \text{ N} \cdot \text{m} \\ H &= 2\pi T N = 2\pi(0.51)(15) = 48.1 \text{ W} \quad \text{Ans.} \\ Q &= 4.85 rcNl = 4.85(28)(0.025)(15)(28) = 1426 \text{ mm}^3/\text{s} \\ Q_s &= 0.71(1426) = 1012 \text{ mm}^3/\text{s} \quad \text{Ans.} \end{aligned}$$

12-10 Consider the bearings as specified by

$$\begin{aligned} \text{minimum } f: & \quad d_{-t_d}^{+0}, \quad b_{-0}^{+t_b} \\ \text{maximum } W: & \quad d_{-t_d}^{+0}, \quad b_{-0}^{+t_b} \end{aligned}$$

and differing only in d and d' .

Preliminaries:

$$l / d = 1$$

$$P = W / (ld) = 700 / (1.25^2) = 448 \text{ psi}$$

$$N = 3600 / 60 = 60 \text{ rev/s}$$

Fig. 12-16:

$$\text{minimum } f: \quad S \doteq 0.08$$

$$\text{maximum } W: \quad S \doteq 0.20$$

Fig. 12-12:

$$\mu = 1.38(10^{-6}) \text{ reyn}$$

$$\mu N/P = 1.38(10^{-6})(60/448) = 0.185(10^{-6})$$

Eq. (12-7):

$$\frac{r}{c} = \sqrt{\frac{S}{\mu N/P}}$$

For minimum f :

$$\frac{r}{c} = \sqrt{\frac{0.08}{0.185(10^{-6})}} = 658$$

$$c = 0.625 / 658 = 0.000950 \doteq 0.001 \text{ in}$$

If this is c_{\min} ,

$$b - d = 2(0.001) = 0.002 \text{ in}$$

The median clearance is

$$\bar{c} = c_{\min} + \frac{t_d + t_b}{2} = 0.001 + \frac{t_d + t_b}{2}$$

and the clearance range for *this* bearing is

$$\Delta c = \frac{t_d + t_b}{2}$$

which is a function only of the tolerances.

For maximum W :

$$\frac{r}{c} = \sqrt{\frac{0.2}{0.185(10^{-6})}} = 1040$$

$$c = 0.625 / 1040 = 0.000600 \doteq 0.0005 \text{ in}$$

If this is c_{\min}

$$b - d' = 2c_{\min} = 2(0.0005) = 0.001 \text{ in}$$

$$\bar{c} = c_{\min} + \frac{t_d + t_b}{2} = 0.0005 + \frac{t_d + t_b}{2}$$

$$\Delta c = \frac{t_d + t_b}{2}$$

The difference (mean) in clearance between the *two* clearance ranges, c_{range} , is

$$c_{\text{range}} = 0.001 + \frac{t_d + t_b}{2} - \left(0.0005 + \frac{t_d + t_b}{2} \right)$$

$$= 0.0005 \text{ in}$$

For the minimum f bearing

$$b - d = 0.002 \text{ in}$$

or

$$d = b - 0.002 \text{ in}$$

For the maximum W bearing

$$d' = b - 0.001 \text{ in}$$

For the same b , t_b and t_d , we need to change the journal diameter by 0.001 in.

$$d' - d = b - 0.001 - (b - 0.002)$$

$$= 0.001 \text{ in}$$

Increasing d of the minimum friction bearing by 0.001 in, defines d' of the maximum load bearing. Thus, the clearance range provides for bearing dimensions which are attainable in manufacturing. *Ans.*

12-11 Given: SAE 40, $N = 10 \text{ rev/s}$, $T_s = 140^\circ\text{F}$, $l/d = 1$, $d = 3.000 \text{ in}$, $b = 3.003 \text{ in}$, $W = 675 \text{ lbf}$.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.003 - 3}{2} = 0.0015 \text{ in}$$

$$r = d / 2 = 3 / 2 = 1.5 \text{ in}$$

$$r / c = 1.5 / 0.0015 = 1000$$

$$P = \frac{W}{ld} = \frac{675}{3(3)} = 75 \text{ psi}$$

Trial #1: From Figure 12-12 for $T = 160^\circ\text{F}$, $\mu = 3.5 \mu \text{ reyn}$,

$$\Delta T = 2(160 - 140) = 40^\circ\text{F}$$

$$S = \left(\frac{r}{c} \right)^2 \frac{\mu N}{P} = 1000^2 \left[\frac{3.5(10^{-6})(10)}{75} \right] = 0.4667$$

From Fig. 12-24,

$$\frac{9.70\Delta T}{P} = 0.349\ 109 + 6.009\ 40(0.4667) + 0.047\ 467(0.4667)^2 = 3.16$$

$$\Delta T = 3.16 \frac{P}{9.70} = 3.16 \frac{75}{9.70} = 24.4^\circ\text{F}$$

Discrepancy = $40 - 24.4 = 15.6^\circ\text{F}$

Trial #2: $T = 150^\circ\text{F}$, $\mu = 4.5\ \mu\ \text{reyn}$,

$$\Delta T = 2(150 - 140) = 20^\circ\text{F}$$

$$S = 1000^2 \left[\frac{4.5(10^{-6})10}{75} \right] = 0.6$$

From Fig. 12-24,

$$\frac{9.70\Delta T}{P} = 0.349\ 109 + 6.009\ 40(0.6) + 0.047\ 467(0.6)^2 = 3.97$$

$$\Delta T = 3.97 \frac{P}{9.70} = 3.97 \frac{75}{9.70} = 30.7^\circ\text{F}$$

Discrepancy = $20 - 30.7 = -10.7^\circ\text{F}$

Trial #3: $T = 154^\circ\text{F}$, $\mu = 4\ \mu\ \text{reyn}$,

$$\Delta T = 2(154 - 140) = 28^\circ\text{F}$$

$$S = 1000^2 \left[\frac{4(10^{-6})10}{75} \right] = 0.533$$

From Fig. 12-24,

$$\frac{9.70\Delta T}{P} = 0.349\ 109 + 6.009\ 40(0.533) + 0.047\ 467(0.533)^2 = 3.57$$

$$\Delta T = 3.57 \frac{P}{9.70} = 3.57 \frac{75}{9.70} = 27.6^\circ\text{F}$$

Discrepancy = $28 - 27.6 = 0.4^\circ\text{F}$ *O.K.*

$$T_{\text{av}} = 140 + 28/2 = 154^\circ\text{F} \quad \text{Ans.}$$

$$T_1 = T_{\text{av}} - \Delta T / 2 = 154 - (28 / 2) = 140^\circ\text{F}$$

$$T_2 = T_{\text{av}} + \Delta T / 2 = 154 + (28 / 2) = 168^\circ\text{F}$$

$$S = 0.4$$

From Figures 12-16, 12-18, to 12-20:

$$\frac{h_0}{c} = 0.75, \quad \frac{fr}{c} = 11, \quad \frac{Q}{rcNl} = 3.6, \quad \frac{Q_s}{Q} = 0.33$$

$$h_0 = 0.75(0.0015) = 0.00113 \text{ in} \quad \text{Ans.}$$

$$f = \frac{11}{1000} = 0.011$$

$$T = fWr = 0.0075(3)(40) = 0.9 \text{ N} \cdot \text{m}$$

$$H_{\text{loss}} = \frac{2\pi fWrN}{778(12)} = \frac{2\pi(0.011)675(1.5)10}{778(12)} = 0.075 \text{ Btu/s} \quad \text{Ans.}$$

$$Q = 3.6rcNl = 3.6(1.5)0.0015(10)3 = 0.243 \text{ in}^3/\text{s} \quad \text{Ans.}$$

$$Q_s = 0.33(0.243) = 0.0802 \text{ in}^3/\text{s} \quad \text{Ans.}$$

12-12 Given: $d = 2.5$ in, $b = 2.504$ in, $c_{\min} = 0.002$ in, $W = 1200$ lbf, SAE = 20, $T_s = 110^\circ\text{F}$, $N = 1120$ rev/min, and $l = 2.5$ in.

$$P = W/(ld) = 1200/(2.5)^2 = 192 \text{ psi}, \quad N = 1120/60 = 18.67 \text{ rev/s}$$

For a trial film temperature, let $T_f = 150^\circ\text{F}$

Table 12-1: $\mu' = 0.0136 \exp[1271.6/(150 + 95)] = 2.441 \mu \text{ reyn}$

$$\text{Eq. (12-7):} \quad S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = \left(\frac{2.5/2}{0.002}\right)^2 \frac{2.441(10^{-6})18.67}{192} = 0.927$$

Fig. 12-24:

$$\Delta T = \frac{192}{9.70} \left[0.349 \cdot 109 + 6.009 \cdot 40(0.0927) + 0.047 \cdot 467(0.0927^2) \right]$$

$$= 17.9^\circ\text{F}$$

$$T_{\text{av}} = T_s + \frac{\Delta T}{2} = 110 + \frac{17.9}{2} = 119.0^\circ\text{F}$$

$$T_f - T_{\text{av}} = 150 - 119.0 = 31.0^\circ\text{F}$$

which is not 0.1 or less, therefore try averaging for the new trial film temperature, let

$$(T_f)_{\text{new}} = \frac{150 + 119.0}{2} = 134.5^\circ\text{F}$$

Proceed with additional trials using a spreadsheet (table also shows the first trial)

Trial	T_f	μ'	S	ΔT	T_{av}	$T_f - T_{av}$	New T_f
	150.0	2.441	0.0927	17.9	119.0	31.0	134.5
	134.5	3.466	0.1317	22.6	121.3	13.2	127.9
	127.9	4.084	0.1551	25.4	122.7	5.2	125.3
	125.3	4.369	0.1659	26.7	123.3	2.0	124.3
	124.3	4.485	0.1704	27.2	123.6	0.7	124.0
	124.0	4.521	0.1717	27.4	123.7	0.3	123.8
	123.8	4.545	0.1726	27.5	123.7	0.1	123.8

Note that the convergence begins rapidly. There are ways to speed this, but at this point they would only add complexity.

(a) $\mu' = 4.545(10^{-6})$, $S = 0.1726$

From Fig. 12-16: $\frac{h_0}{c} = 0.482$, $h_0 = 0.482(0.002) = 0.000964$ in

From Fig. 12-17: $\phi = 56^\circ$ *Ans.*

(b) $e = c - h_0 = 0.002 - 0.000964 = 0.00104$ in *Ans.*

(c) From Fig. 12-18: $\frac{f r}{c} = 4.10$, $f = 4.10(0.002/1.25) = 0.00656$ *Ans.*

(d) $T = f W r = 0.00656(1200)(1.25) = 9.84$ lbf · in

$$H = \frac{2\pi T N}{778(12)} = \frac{2\pi(9.84)(1120/60)}{778(12)} = 0.124 \text{ Btu/s} \quad \text{Ans.}$$

(e) From Fig. 12-19: $\frac{Q}{rcNl} = 4.16$

$$Q = 4.16(1.25)(0.002) \left(\frac{1120}{60} \right) (2.5) = 0.485 \text{ in}^3/\text{s} \quad \text{Ans.}$$

From Fig. 12-20: $\frac{Q_s}{Q} = 0.6$, $Q_s = 0.6(0.485) = 0.291 \text{ in}^3/\text{s} \quad \text{Ans.}$

(f) From Fig. 12-21: $\frac{P}{p_{\max}} = 0.45$, $p_{\max} = \frac{W / (ld)}{0.45} = \frac{1200 / 2.5^2}{0.45} = 427 \text{ psi} \quad \text{Ans.}$

From Fig. 12-22: $\phi_{p_{\max}} = 16^\circ$ *Ans.*

(g) From Fig. 12-22: $\phi_{p_0} = 82^\circ$ Ans.

(h) From the trial table, $T_f = 123.8^\circ\text{F}$ Ans.

(i) With $\Delta T = 27.5^\circ\text{F}$ from the trial table, $T_s + \Delta T = 110 + 27.5 = 137.5^\circ\text{F}$ Ans.

12-13 Given: $d = 1.250$ in, $t_d = 0.001$ in, $b = 1.252$ in, $t_b = 0.003$ in, $l = 1.25$ in, $W = 250$ lbf, $N = 1750$ rev/min, SAE 10 lubricant, sump temperature $T_s = 120^\circ\text{F}$.

$$P = W/(ld) = 250/1.25^2 = 160 \text{ psi}, \quad N = 1750/60 = 29.17 \text{ rev/s}$$

For the clearance, $c = 0.002 \pm 0.001$ in. Thus, $c_{\min} = 0.001$ in, $c_{\text{median}} = 0.002$ in, and $c_{\max} = 0.003$ in.

For $c_{\min} = 0.001$ in, start with a trial film temperature of $T_f = 135^\circ\text{F}$

Table 12-1: $\mu' = 0.0158 \exp[1157.5/(135 + 95)] = 2.423 \mu \text{ reyn}$

$$\text{Eq. (12-7): } S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = \left(\frac{1.25/2}{0.001}\right)^2 \frac{2.423(10^{-6})29.17}{160} = 0.1725$$

Fig. 12-24:

$$\Delta T = \frac{160}{9.70} [0.349 109 + 6.009 40(0.1725) + 0.047 467(0.1725^2)] \\ = 22.9^\circ\text{F}$$

$$T_{\text{av}} = T_s + \frac{\Delta T}{2} = 120 + \frac{22.9}{2} = 131.4^\circ\text{F}$$

$$T_f - T_{\text{av}} = 135 - 131.4 = 3.6^\circ\text{F}$$

which is not 0.1 or less, therefore try averaging for the new trial film temperature, let

$$(T_f)_{\text{new}} = \frac{135 + 131.4}{2} = 133.2^\circ\text{F}$$

Proceed with additional trials using a spreadsheet (table also shows the first trial)

Trial	T_f	μ'	S	ΔT	T_{av}	$T_f - T_{\text{av}}$	New T_f
135.0	2.423	0.1725	22.9	131.4	3.6	133.2	
133.2	2.521	0.1795	23.6	131.8	1.4	132.5	
132.5	2.560	0.1823	23.9	131.9	0.6	132.2	
132.2	2.578	0.1836	24.0	132.0	0.2	132.1	
132.1	2.583	0.1840	24.0	132.0	0.1	132.1	

With $T_f = 132.1^\circ\text{F}$, $\Delta T = 24.0^\circ\text{F}$, $\mu' = 2.583 \mu \text{ reyn}$, $S = 0.1840$,

$$T_{\max} = T_s + \Delta T = 120 + 24.0 = 144.0^\circ\text{F}$$

Fig. 12-16: $h_0/c = 0.50$, $h_0 = 0.50(0.001) = 0.00050 \text{ in}$

$$\epsilon = 1 - h_0/c = 1 - 0.50 = 0.05 \text{ in}$$

Fig. 12-18: $rf/c = 4.25$, $f = 4.25/(0.625/0.001) = 0.0068$

Fig. 12-19: $Q/(rcNI) = 4.13$, $Q = 4.13(0.625)0.001(29.17)1.25 = 0.0941 \text{ in}^3/\text{s}$

Fig. 12-20: $Q_s/Q = 0.58$, $Q_s = 0.58(0.0941) = 0.0546 \text{ in}^3/\text{s}$

The above can be repeated for $c_{\text{median}} = 0.002 \text{ in}$, and $c_{\text{max}} = 0.003 \text{ in}$. The results are shown below.

	c_{\min} 0.001 in	c_{median} 0.002 in	c_{\max} 0.003 in
T_f	132.1	125.6	124.1
μ'	2.583	3.002	3.112
S	0.184	0.0534	0.0246
ΔT	24.0	11.1	8.2
T_{\max}	144.0	131.1	128.2
h_0/c	0.5	0.23	0.125
h_0	0.00050	0.00069	0.00038
ϵ	0.50	0.77	0.88
fr/c	4.25	1.8	1.22
f	0.0068	0.0058	0.0059
$Q/(rcNI)$	4.13	4.55	4.7
Q	0.0941	0.207	0.321
Q_s/Q	0.58	0.82	0.90
Q_s	0.0546	0.170	0.289

12-14 Computer programs will vary.

12-15 Note to the Instructor: In the first printing of the 9th edition, the l/d ratio and the lubrication constant α were omitted. The values to use are $l/d = 1$, and $\alpha = 1$. This will be updated in the next printing. We apologize for any inconvenience this may have caused.

In a step-by-step fashion, we are building a skill for natural circulation bearings.

- Given the average film temperature, establish the bearing properties.
- Given a sump temperature, find the average film temperature, then establish the bearing properties.
- Now we acknowledge the environmental temperature's role in establishing the sump temperature. Sec. 12-9 and Ex. 12-5 address this problem.

Given: $d_{\max} = 2.500$ in, $b_{\min} = 2.504$ in, $l/d = 1$, $N = 1120$ rev/min, SAE 20 lubricant, $W = 300$ lbf, $A = 60$ in², $T_{\infty} = 70^{\circ}\text{F}$, and $\alpha = 1$.

600 lbf load with minimal clearance: We will start by using $W = 600$ lbf ($n_d = 2$). The task is to iteratively find the average film temperature, T_f , which makes H_{gen} and H_{loss} equal.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{2.504 - 2.500}{2} = 0.002 \text{ in}$$

$$N = 1120/60 = 18.67 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{600}{2.5^2} = 96 \text{ psi}$$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = \left(\frac{1.25}{0.002}\right)^2 \frac{\mu'(10^{-6})18.67}{96} = 0.0760\mu'$$

Table 12-1: $\mu' = 0.0136 \exp[1271.6/(T_f + 95)]$

$$\begin{aligned} H_{\text{gen}} &= \frac{2545}{1050} W N c \left(\frac{f r}{c}\right) = \frac{2545}{1050} (600) 18.67 (0.002) \frac{f r}{c} \\ &= 54.3 \frac{f r}{c} \end{aligned}$$

$$\begin{aligned} H_{\text{loss}} &= \frac{\dot{h}_{\text{CR}} A}{\alpha + 1} (T_f - T_{\infty}) = \frac{2.7(60 / 144)}{1 + 1} (T_f - 70) \\ &= 0.5625 (T_f - 70) \end{aligned}$$

Start with trial values of T_f of 220 and 240°F.

Trial T_f	μ'	S	$f r/c$	H_{gen}	H_{loss}
220	0.770	0.059	1.9	103.2	84.4
240	0.605	0.046	1.7	92.3	95.6

As a linear approximation, let $H_{\text{gen}} = mT_f + b$. Substituting the two sets of values of T_f and H_{gen} we find that $H_{\text{gen}} = -0.545 T_f + 223.1$. Setting this equal to H_{loss} and solving for T_f gives $T_f = 237^{\circ}\text{F}$.

Trial T_f	μ'	S	fr/c	H_{gen}	H_{loss}
237	0.627	0.048	1.73	93.9	94.0

which is satisfactory.

Table 12-16: $h_0/c = 0.21$, $h_0 = 0.21 (0.002) = 0.00042$ in

Fig. 12-24:

$$\Delta T = \frac{96}{9.7} \left[0.349109 + 6.0094(0.048) + 0.047467(0.048^2) \right]$$

$$= 6.31^\circ\text{F}$$

$$T_1 = T_s = T_f - \Delta T = 237 - 6.31/2 = 233.8^\circ\text{F}$$

$$T_{\text{max}} = T_1 + \Delta T = 233.8 + 6.31 = 240.1^\circ\text{F}$$

Trumpler's design criteria:

$$0.002 + 0.00004d = 0.002 + 0.00004(2.5) = 0.00030 \text{ in} < h_0 \quad O.K.$$

$$T_{\text{max}} = 240.1^\circ\text{F} < 250^\circ\text{F} \quad O.K.$$

$$\frac{W_{st}}{ld} = \frac{300}{2.5^2} = 48 \text{ psi} < 300 \text{ psi} \quad O.K.$$

$$n_d = 2 \text{ (assessed at } W = 600 \text{ lbf)} \quad O.K.$$

We see that the design passes Trumpler's criteria and is deemed acceptable.

For an operating load of $W = 300$ lbf, it can be shown that $T_f = 219.3^\circ\text{F}$, $\mu' = 0.78$, $S = 0.118$, $fr/c = 3.09$, $H_{\text{gen}} = H_{\text{loss}} = 84$ Btu/h, $h_0 =$, $\Delta T = 10.5^\circ\text{F}$, $T_1 = 224.6^\circ\text{F}$, and $T_{\text{max}} = 235.1^\circ\text{F}$.

12-16 Given: $d = 3.500^{+0.000}_{-0.001}$ in, $b = 3.505^{+0.005}_{-0.000}$ in, SAE 30, $T_s = 120^\circ\text{F}$, $p_s = 50$ psi, $N = 2000/60 = 33.33$ rev/s, $W = 4600$ lbf, bearing length = 2 in, groove width = 0.250 in, and $H_{\text{loss}} \leq 5000$ Btu/hr.

$$c_{\text{min}} = \frac{b_{\text{min}} - d_{\text{max}}}{2} = \frac{3.505 - 3.500}{2} = 0.0025 \text{ in}$$

$$r = d/2 = 3.500/2 = 1.750 \text{ in}$$

$$r/c = 1.750/0.0025 = 700$$

$$l' = (2 - 0.25)/2 = 0.875 \text{ in}$$

$$l' / d = 0.875 / 3.500 = 0.25$$

$$P = \frac{W}{4rl'} = \frac{4600}{4(1.750)0.875} = 751 \text{ psi}$$

Trial #1: Choose $(T_f)_1 = 150^\circ\text{F}$. From Table 12-1,

$$\mu' = 0.0141 \exp[1360.0 / (150 + 95)] = 3.63 \mu \text{ reyn}$$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 700^2 \left[\frac{3.63(10^{-6})(33.33)}{751} \right] = 0.0789$$

From Figs. 12-16 and 12-18: $\epsilon = 0.9$, $fr/c = 3.6$

From Eq. (12-24),

$$\begin{aligned} \Delta T &= \frac{0.0123(fr/c)SW^2}{(1 + 1.5\epsilon^2)p_s r^4} \\ &= \frac{0.0123(3.6)0.0789(4600^2)}{[1 + 1.5(0.9)^2]50(1.750^4)} = 71.2^\circ\text{F} \end{aligned}$$

$$T_{av} = T_s + \Delta T / 2 = 120 + 71.2 / 2 = 155.6^\circ\text{F}$$

Trial #2: Choose $(T_f)_2 = 160^\circ\text{F}$. From Table 12-1

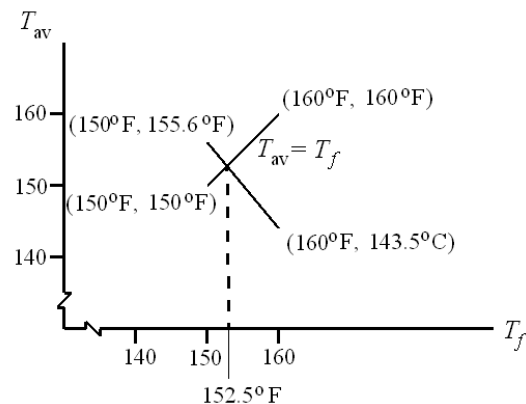
$$\mu' = 0.0141 \exp[1360.0 / (160 + 95)] = 2.92 \mu \text{ reyn}$$

$$S = 0.0789 \left(\frac{2.92}{3.63} \right) = 0.0635$$

From Figs. 12-16 and 12-18: $\epsilon = 0.915$, $fr/c = 3$

$$\Delta T = \frac{0.0123(3)0.0635(4600^2)}{[1 + 1.5(0.915^2)]50(1.750^4)} = 46.9^\circ\text{F}$$

$$T_{av} = 120 + 46.9 / 2 = 143.5^\circ\text{F}$$



Trial #3: Thus, the plot gives $(T_f)_3 = 152.5^\circ\text{F}$. From Table 12-1

$$\mu' = 0.0141 \exp[1360.0/(152.5 + 95)] = 3.43 \mu \text{ reyn}$$

$$S = 0.0789 \left(\frac{3.43}{3.63} \right) = 0.0746$$

From Figs. 12-16 and 12-18: $\epsilon = 0.905$, $f r / c = 3.4$

$$\Delta T = \frac{0.0123(3.4)0.0746(4600^2)}{[1 + 1.5(0.905^2)]50(1.750^4)} = 63.2^\circ\text{F}$$

$$T_{\text{av}} = 120 + 63.2/2 = 151.6^\circ\text{F}$$

Result is close. Choose $\bar{T}_f = \frac{152.5 + 151.6}{2} = 152.1^\circ\text{F}$ Try 152°F

Table 12-1: $\mu' = 0.0141 \exp[1360.0/(152 + 95)] = 3.47 \mu \text{ reyn}$

$$S = 0.0789 \left(\frac{3.47}{3.63} \right) = 0.0754$$

$$\frac{f r}{c} = 3.4, \quad \epsilon = 0.902, \quad \frac{h_0}{c} = 0.098$$

$$\Delta T = \frac{0.0123(3.4)0.0754(4600^2)}{[1 + 1.5(0.902^2)]50(1.750^4)} = 64.1^\circ\text{F}$$

$$T_{\text{av}} = 120 + 64.1 / 2 = 152.1^\circ\text{F} \quad \text{O.K.}$$

$$h_0 = 0.098(0.0025) = 0.000245 \text{ in}$$

$$T_{\text{max}} = T_s + \Delta T = 120 + 64.1 = 184.1^\circ\text{F}$$

Eq. (12-22):

$$Q_s = \frac{\pi p_s r c^3}{3 \mu l'} (1 + 1.5 \epsilon^2) = \frac{\pi (50) 1.750 (0.0025^3)}{3 (3.47) 10^{-6} (0.875)} [1 + 1.5 (0.902^2)]$$

$$= 1.047 \text{ in}^3/\text{s}$$

$$H_{\text{loss}} = \rho C_p Q_s \Delta T = 0.0311(0.42)1.047(64.1) = 0.877 \text{ Btu/s}$$

$$= 0.877(60^2) = 3160 \text{ Btu/h} \quad \text{O.K.}$$

Trumpler's design criteria:

$$0.0002 + 0.00004(3.5) = 0.00034 \text{ in} > 0.000245 \quad \text{Not O.K.}$$

$$T_{\text{max}} = 184.1^\circ\text{F} < 250^\circ\text{F} \quad \text{O.K.}$$

$$P_{st} = 751 \text{ psi} > 300 \text{ psi} \quad \text{Not O.K.}$$

$$n = 1, \text{ as done} \quad \text{Not O.K.}$$

12-17 Given: $d = 50.00_{-0.05}^{+0.00}$ mm, $b = 50.084_{-0.000}^{+0.010}$ mm, SAE 30, $T_s = 55^\circ\text{C}$, $p_s = 200$ kPa, $N = 2880/60 = 48$ rev/s, $W = 10$ kN, bearing length = 55 mm, groove width = 5 mm, and $H_{\text{loss}} \leq 300$ W.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{50.084 - 50}{2} = 0.042 \text{ mm}$$

$$r = d/2 = 50/2 = 25 \text{ mm}$$

$$r/c = 25/0.042 = 595$$

$$l' = (55 - 5)/2 = 25 \text{ mm}$$

$$l'/d = 25/50 = 0.5$$

$$P = \frac{W}{4rl'} = \frac{10(10^3)}{4(25)25} = 4 \text{ MPa}$$

Trial #1: Choose $(T_f)_1 = 79^\circ\text{C}$. From Fig. 12-13, $\mu = 13 \text{ MPa} \cdot \text{s}$.

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 595^2 \left[\frac{13(10^{-3})(48)}{4(10^6)} \right] = 0.0552$$

From Figs. 12-16 and 12-18: $\epsilon = 0.85$, $fr/c = 2.3$

From Eq. (12-25),

$$\begin{aligned} \Delta T &= \frac{978(10^6) (fr/c) S W^2}{1 + 1.5\epsilon^2 p_s r^4} \\ &= \frac{978(10^6)}{1 + 1.5(0.85)^2} \left[\frac{2.3(0.0552)(10^2)}{200(25)^4} \right] = 76.3^\circ\text{C} \end{aligned}$$

$$T_{\text{av}} = T_s + \Delta T/2 = 55 + 76.3/2 = 93.2^\circ\text{C}$$

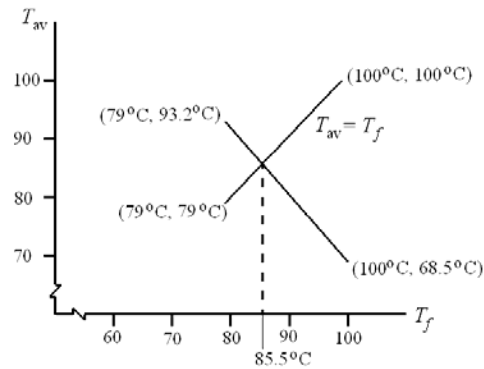
Trial #2: Choose $(T_f)_2 = 100^\circ\text{C}$. From Fig. 12-13, $\mu = 7 \text{ MPa} \cdot \text{s}$.

$$S = 0.0552 \left(\frac{7}{13} \right) = 0.0297$$

From Figs. 12-16 and 12-18: $\epsilon = 0.90$, $fr/c = 1.6$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.9)^2} \left[\frac{1.6(0.0297)(10^2)}{200(25)^4} \right] = 26.9^\circ\text{C}$$

$$T_{\text{av}} = 55 + 26.9/2 = 68.5^\circ\text{C}$$



Trial #3: Thus, the plot gives $(T_f)_3 = 85.5^\circ\text{C}$. From Fig. 12-13, $\mu = 10.5 \text{ MPa} \cdot \text{s}$.

$$S = 0.0552 \left(\frac{10.5}{13} \right) = 0.0446$$

From Figs. 12-16 and 12-18: $\epsilon = 0.87$, $fr/c = 2.2$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.87^2)} \left[\frac{2.2(0.0457)(10^2)}{200(25)^4} \right] = 58.9^\circ\text{C}$$

$$T_{\text{av}} = 55 + 58.9/2 = 84.5^\circ\text{C}$$

Result is close. Choose $\bar{T}_f = \frac{85.5 + 84.5}{2} = 85^\circ\text{C}$

Fig. 12-13: $\mu = 10.5 \text{ MPa} \cdot \text{s}$

$$S = 0.0552 \left(\frac{10.5}{13} \right) = 0.0446$$

$$\epsilon = 0.87, \quad \frac{fr}{c} = 2.2, \quad \frac{h_0}{c} = 0.13$$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.87^2)} \left[\frac{2.2(0.0457)(10^2)}{200(25^4)} \right] = 58.9^\circ\text{C} \quad \text{or} \quad 138^\circ\text{F}$$

$$T_{\text{av}} = 55 + 58.9 / 2 = 84.5^\circ\text{C} \quad \text{O.K.}$$

From Eq. (12-22)

$$h_0 = 0.13(0.042) = 0.00546 \text{ mm or } 0.000215 \text{ in}$$

$$T_{\text{max}} = T_s + \Delta T = 55 + 58.9 = 113.9^\circ\text{C} \quad \text{or} \quad 237^\circ\text{F}$$

$$Q_s = (1 + 1.5\epsilon^2) \frac{\pi p_s r c^3}{3\mu l'} = \left[1 + 1.5(0.87^2) \right] \left[\frac{\pi (200) 25 (0.042^3)}{3(10.5) 10^{-6} (25)} \right]$$

$$= 3156 \text{ mm}^3/\text{s} = 3156 (25.4^{-3}) = 0.193 \text{ in}^3/\text{s}$$

$$H_{\text{loss}} = \rho C_p Q_s \Delta T = 0.0311(0.42)0.193(138) = 0.348 \text{ Btu/s}$$

$$= 1.05(0.348) = 0.365 \text{ kW} = 365 \text{ W} \quad \text{not O.K.}$$

Trumpler's design criteria:

$$0.0002 + 0.00004(50/25.4) = 0.000279 \text{ in} > h_0 \quad \text{Not O.K.}$$

$$T_{\max} = 237^\circ\text{F} \quad \text{O.K.}$$

$$P_{st} = 4000 \text{ kPa} \quad \text{or} \quad 581 \text{ psi} > 300 \text{ psi} \quad \text{Not O.K.}$$

$$n = 1, \quad \text{as done} \quad \text{Not O.K.}$$

12-18 So far, we've performed elements of the design task. Now let's do it more completely.

The values of the unilateral tolerances, t_b and t_d , reflect the routine capabilities of the bushing vendor and the in-house capabilities. While the designer has to live with these, his approach should not depend on them. They can be incorporated later.

First we shall find the minimum size of the journal which satisfies Trumpler's constraint of $P_{st} \leq 300$ psi.

$$P_{st} = \frac{W}{2dl'} \leq 300$$

$$\frac{W}{2d^2l'/d} \leq 300 \Rightarrow d \geq \sqrt{\frac{W}{600(l'/d)}}$$

$$d_{\min} = \sqrt{\frac{900}{2(300)(0.5)}} = 1.73 \text{ in}$$

In this problem we will take journal diameter as the nominal value and the bushing bore as a variable. In the next problem, we will take the bushing bore as nominal and the journal diameter as free.

To determine where the constraints are, we will set $t_b = t_d = 0$, and thereby shrink the design window to a point.

We set

$$d = 2.000 \text{ in}$$

$$b = d + 2c_{\min} = d + 2c$$

$$n_d = 2 \quad (\text{This makes Trumpler's } n_d \leq 2 \text{ tight})$$

and construct a table.

c	b	d	\bar{T}_f^*	T_{\max}	h_o	P_{st}	T_{\max}	n	fom
0.0010	2.0020	2	215.50	312.0	×	✓	×	✓	-5.74
0.0011	2.0022	2	206.75	293.0	×	✓	✓	✓	-6.06
0.0012	2.0024	2	198.50	277.0	×	✓	✓	✓	-6.37
0.0013	2.0026	2	191.40	262.8	×	✓	✓	✓	-6.66
0.0014	2.0028	2	185.23	250.4	×	✓	✓	✓	-6.94
0.0015	2.0030	2	179.80	239.6	×	✓	✓	✓	-7.20
0.0016	2.0032	2	175.00	230.1	×	✓	✓	✓	-7.45
0.0017	2.0034	2	171.13	220.3	×	✓	✓	✓	-7.65
0.0018	2.0036	2	166.92	213.9	✓	✓	✓	✓	-7.91
0.0019	2.0038	2	163.50	206.9	✓	✓	✓	✓	-8.12
0.0020	2.0040	2	160.40	200.6	✓	✓	✓	✓	-8.32

*Sample calculation for the first entry of this column.

Iteration yields: $\bar{T}_f = 215.5^\circ\text{F}$

With $\bar{T}_f = 215.5^\circ\text{F}$, from Table 12-1

$$\mu = 0.0136(10^{-6}) \exp[1271.6 / (215.5 + 95)] = 0.817(10^{-6}) \text{ reyn}$$

$$N = 3000 / 60 = 50 \text{ rev/s}, \quad P = \frac{900}{4} = 225 \text{ psi}$$

$$S = \left(\frac{1}{0.001} \right)^2 \left[\frac{0.817(10^{-6})(50)}{225} \right] = 0.182$$

From Figs. 12-16 and 12-18: $e = 0.7, \quad fr/c = 5.5$

Eq. (12-24):

$$\Delta T_F = \frac{0.0123(5.5)(0.182)(900^2)}{[1 + 1.5(0.7^2)](30)(1^4)} = 191.6^\circ\text{F}$$

$$T_{\text{av}} = 120^\circ\text{F} + \frac{191.6^\circ\text{F}}{2} = 215.8^\circ\text{F} \doteq 215.5^\circ\text{F}$$

For the nominal 2-in bearing, the various clearances show that we have been in contact with the recurving of $(h_o)_{\min}$. The figure of merit (the parasitic friction torque plus the pumping torque negated) is best at $c = 0.0018$ in. For the nominal 2-in bearing, we will place the top of the design window at $c_{\min} = 0.002$ in, and $b = d + 2(0.002) = 2.004$ in. At this point, add the b and d unilateral tolerances:

$$d = 2.000_{-0.001}^{+0.000} \text{ in}, \quad b = 2.004_{-0.000}^{+0.003} \text{ in}$$

Now we can check the performance at c_{\min} , \bar{c} , and c_{\max} . Of immediate interest is the fom of the median clearance assembly, -9.82 , as compared to any other satisfactory bearing ensemble.

If a nominal 1.875 in bearing is possible, construct another table with $t_b = 0$ and $t_d = 0$.

c	b	d	\bar{T}_f	T_{\max}	h_o	P_{st}	T_{\max}	n	fom
0.0020	1.879	1.875	157.2	194.30	×	✓	✓	✓	-7.36
0.0030	1.881	1.875	138.6	157.10	✓	✓	✓	✓	-8.64
0.0035	1.882	1.875	133.5	147.10	✓	✓	✓	✓	-9.05
0.0040	1.883	1.875	130.0	140.10	✓	✓	✓	✓	-9.32
0.0050	1.885	1.875	125.7	131.45	✓	✓	✓	✓	-9.59
0.0055	1.886	1.875	124.4	128.80	✓	✓	✓	✓	-9.63
0.0060	1.887	1.875	123.4	126.80	×	✓	✓	✓	-9.64

The range of clearance is $0.0030 < c < 0.0055$ in. That is enough room to fit in our design window.

$$d = 1.875_{-0.001}^{+0.000} \text{ in}, \quad b = 1.881_{-0.000}^{+0.003} \text{ in}$$

The ensemble median assembly has a fom = -9.31.

We just had room to fit in a design window based upon the $(h_o)_{\min}$ constraint. Further reduction in nominal diameter will preclude any smaller bearings. A table constructed for a $d = 1.750$ in journal will prove this.

We choose the nominal 1.875-in bearing ensemble because it has the largest figure of merit. *Ans.*

12-19 This is the same as Prob. 12-18 but uses design variables of nominal bushing bore b and radial clearance c .

The approach is similar to that of Prob. 12-18 and the tables will change slightly. In the table for a nominal $b = 1.875$ in, note that at $c = 0.003$ in the constraints are “loose.” Set

$$b = 1.875 \text{ in}$$

$$d = 1.875 - 2(0.003) = 1.869 \text{ in}$$

For the ensemble

$$b = 1.875_{-0.001}^{+0.003} \text{ in}, \quad d = 1.869_{-0.001}^{+0.000} \text{ in}$$

Analyze at $c_{\min} = 0.003$, $\bar{c} = 0.004$ in and $c_{\max} = 0.005$ in

At $c_{\min} = 0.003$ in: $\bar{T}_f = 138.4$, $\mu' = 3.160$, $S = 0.0297$, $H_{\text{loss}} = 1035$ Btu/h and the Trumpler conditions are met.

At $\bar{c} = 0.004$ in: $\bar{T}_f = 130^\circ\text{F}$, $\mu' = 3.872$, $S = 0.0205$, $H_{\text{loss}} = 1106$ Btu/h, fom = -9.246

and the Trumpler conditions are *O.K.*

At $c_{\max} = 0.005$ in: $\bar{T}_f = 125.68^\circ\text{F}$, $\mu' = 4.325$, $S = 0.01466$, $H_{\text{loss}} = 1129$ Btu/h and the Trumpler conditions are *O.K.*

The ensemble figure of merit is slightly better; this bearing is *slightly* smaller. The lubricant cooler has sufficient capacity.

12-20 Table 12-1: μ (μ reyn) = $\mu_0 (10^6) \exp [b / (T + 95)]$ b and T in $^\circ\text{F}$

The conversion from μ reyn to mPa·s is given on p. 620. For a temperature of C degrees Celsius, $T = 1.8 C + 32$. Substituting into the above equation gives

$$\begin{aligned} \mu \text{ (mPa}\cdot\text{s)} &= 6.89 \mu_0 (10^6) \exp [b / (1.8 C + 32 + 95)] \\ &= 6.89 \mu_0 (10^6) \exp [b / (1.8 C + 127)] \quad \text{Ans.} \end{aligned}$$

For SAE 50 oil at 70°C , from Table 12-1, $\mu_0 = 0.0170 (10^{-6})$ reyn, and $b = 1509.6^\circ\text{F}$. From the equation,

$$\begin{aligned} \mu &= 6.89(0.0170) 10^{-6} (10^6) \exp \{1509.6 / [1.8(70) + 127]\} \\ &= 45.7 \text{ mPa}\cdot\text{s} \quad \text{Ans.} \end{aligned}$$

From Fig. 12-13, $\mu = 39$ mPa·s *Ans.*

The figure gives a value of about 15 % lower than the equation.

12-21 Originally

$$d = 2.000_{-0.001}^{+0.000} \text{ in, } b = 2.005_{-0.000}^{+0.003} \text{ in}$$

Doubled,

$$d = 4.000_{-0.002}^{+0.000} \text{ in, } b = 4.010_{-0.000}^{+0.006} \text{ in}$$

The radial load quadrupled to 3600 lbf when the analyses for parts (a) and (b) were carried out. Some of the results are:

Part	\bar{c}	μ'	S	T_f	fr/c	Q_s	h_0/c	e	H_{loss}	h_0	Trumpler	
											h_0	f
(a)	0.007	3.416	0.0310	135.1	0.1612	6.56	0.1032	0.897	9898	0.000 722	0.000 360	0.005 67
(b)	0.0035	3.416	0.0310	135.1	0.1612	0.870	0.1032	0.897	1237	0.000 361	0.000 280	0.005 67

The side flow Q_s differs because there is a c^3 term and consequently an 8-fold increase. H_{loss} is related by a 9898/1237 or an 8-fold increase. The existing h_0 is related by a 2-fold increase. Trumpler's $(h_0)_{\min}$ is related by a 1.286-fold increase.

12-22 Given: Oiles SP 500 alloy brass bushing, $L = 0.75$ in, $D = 0.75$ in, $T_\infty = 70^\circ\text{F}$, $F = 400$ lbf, $N = 250$ rev/min, and $w = 0.004$ in.

Table 12-8: $K = 0.6(10^{-10}) \text{ in}^3 \cdot \text{min}/(\text{lbf} \cdot \text{ft} \cdot \text{h})$

$$P = F/(DL) = 400/[0.75(0.75)] = 711 \text{ psi}$$

$$V = \pi DN/12 = \pi(0.75)250/12 = 49.1 \text{ ft/min}$$

Tables 12-10 and 12-11: $f_1 = 1.8$, $f_2 = 1.0$

Table 12-12: $PV_{\max} = 46\,700$ psi·ft/min, $P_{\max} = 3560$ psi, $V_{\max} = 100$ ft/min

$$P_{\max} = \frac{4}{\pi} \frac{F}{DL} = \frac{4}{\pi} \frac{400}{0.75^2} = 905 \text{ psi} < 3560 \text{ psi } O.K.$$

$$PV = 711(49.1) = 34\,910 \text{ psi} \cdot \text{ft/min} < 46\,700 \text{ psi} \cdot \text{ft/min } O.K.$$

Eq. (12-32) can be written as

$$w = f_1 f_2 K \frac{4}{\pi} \frac{F}{DL} V t$$

Solving for t ,

$$t = \frac{\pi DL w}{4 f_1 f_2 K V F} = \frac{\pi(0.75)0.75(0.004)}{4(1.8)1.0(0.6)10^{-10}(49.1)400}$$

$$= 833.1 \text{ h} = 833.1(60) = 49\,900 \text{ min}$$

$$\text{Cycles} = Nt = 250(49\,900) = 12.5(10^6) \text{ cycles } \quad \text{Ans.}$$

12-23 Given: Oiles SP 500 alloy brass bushing, $w_{\max} = 0.002$ in for 1000 h, $N = 400$ rev/min, $F = 100$ lbf, $h_{\text{CR}} = 2.7$ Btu/(h·ft²·°F), $T_{\max} = 300^\circ\text{F}$, $f_s = 0.03$, and $n_d = 2$.

Estimate bushing length with $f_1 = f_2 = 1$, and $K = 0.6(10^{-10}) \text{ in}^3 \cdot \text{min}/(\text{lbf} \cdot \text{ft} \cdot \text{h})$

Using Eq. (12-32) with $n_d F$ for F ,

$$L = \frac{f_1 f_2 K n_d F N t}{3w} = \frac{1(1)(0.6)(10^{-10})(2)(100)(400)(1000)}{3(0.002)} = 0.80 \text{ in}$$

From Eq. (12-38), with $f_s = 0.03$ from Table 12-9 applying $n_d = 2$ to F

and $\dot{h}_{CR} = 2.7 \text{ Btu}/(\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})$

$$L \doteq \frac{720 f_s n_d F N}{J \dot{h}_{CR} (T_f - T_\infty)} = \frac{720(0.03)(2)(100)(400)}{778(2.7)(300 - 70)} = 3.58 \text{ in}$$

$$0.80 \leq L \leq 3.58 \text{ in}$$

Trial 1: Let $L = 1 \text{ in}$, $D = 1 \text{ in}$

$$P_{\max} = \frac{4 n_d F}{\pi DL} = \frac{4(2)(100)}{\pi(1)(1)} = 255 \text{ psi} < 3560 \text{ psi} \quad O.K.$$

$$P = \frac{n_d F}{DL} = \frac{2(100)}{1(1)} = 200 \text{ psi}$$

$$V = \frac{\pi DN}{12} = \frac{\pi(1)(400)}{12} = 104.7 \text{ ft/min} > 100 \text{ ft/min} \quad \text{Not } O.K.$$

Trial 2: Try $D = 7/8 \text{ in} = 0.875 \text{ in}$, $L = 1 \text{ in}$

$$P_{\max} = \frac{4(2)(100)}{\pi(0.875)(1)} = 291 \text{ psi} < 3560 \text{ psi} \quad O.K.$$

$$P = \frac{2(100)}{0.875(1)} = 229 \text{ psi}$$

$$V = \frac{\pi(0.875)(400)}{12} = 91.6 \text{ ft/min} < 100 \text{ ft/min} \quad O.K.$$

$$PV = 229(91.6) = 20\,976 \text{ psi} \cdot \text{ft/min} < 46\,700 \text{ psi} \cdot \text{ft/min} \quad O.K.$$

V	f_1	
33	1.3	
91.6	f_1	$\Rightarrow f_1 = 1.3 + (1.8 - 1.3) \left(\frac{91.6 - 33}{100 - 33} \right) = 1.74$
100	1.8	$L_{\text{new}} = f_1 L_{\text{old}} = 1.74(0.80) = 1.39 \text{ in}$

Trial 3: Try $D = 7/8 \text{ in} = 0.875 \text{ in}$, $L = 1.5 \text{ in}$

$$P_{\max} = \frac{4(2)(100)}{\pi(0.875)(1.5)} = 194 \text{ psi} < 3560 \text{ psi} \quad O.K.$$

$$P = \frac{2(100)}{0.875(1.5)} = 152 \text{ psi}, \quad V = 91.6 \text{ ft/min}$$

$$PV = 152(91.6) = 13\,923 \text{ psi} \cdot \text{ft/min} < 46\,700 \text{ psi} \cdot \text{ft/min} \quad O.K.$$

$D = 7/8 \text{ in}$, $L = 1.5 \text{ in}$ is acceptable *Ans.*

Suggestion: Try smaller sizes.

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