

Chapter 12

12-1 Given $d_{\max} = 1.000$ in and $b_{\min} = 1.0015$ in, the minimum radial clearance is

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{1.0015 - 1.000}{2} = 0.00075 \text{ in}$$

Also

$$l/d = 1$$

$$r \doteq 1.000/2 = 0.500$$

$$r/c = 0.500/0.00075 = 667$$

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

$$P = W/(ld) = 250/[(1)(1)] = 250 \text{ psi}$$

Eq. (12-7):
$$S = (667^2) \left[\frac{8(10^{-6})(18.33)}{250} \right] = 0.261$$

Fig. 12-16:
$$h_0/c = 0.595$$

Fig. 12-19:
$$Q/(rcNl) = 3.98$$

Fig. 12-18:
$$fr/c = 5.8$$

Fig. 12-20:
$$Q_s/Q = 0.5$$

$$h_0 = 0.595(0.00075) = 0.000466 \text{ in} \quad \text{Ans.}$$

$$f = \frac{5.8}{r/c} = \frac{5.8}{667} = 0.0087$$

The power loss in Btu/s is

$$H = \frac{2\pi fWrN}{778(12)} = \frac{2\pi(0.0087)(250)(0.5)(18.33)}{778(12)}$$

$$= 0.0134 \text{ Btu/s} \quad \text{Ans.}$$

$$Q = 3.98rcNl = 3.98(0.5)(0.00075)(18.33)(1) = 0.0274 \text{ in}^3/\text{s}$$

$$Q_s = 0.5(0.0274) = 0.0137 \text{ in}^3/\text{s} \quad \text{Ans.}$$

12-2

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{1.252 - 1.250}{2} = 0.001 \text{ in}$$

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

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

$$N = 1150/60 = 19.167 \text{ rev/s}$$

$$P = \frac{400}{1.25(2.5)} = 128 \text{ psi}$$

$$l/d = 2.5/1.25 = 2$$

$$S = \frac{(625^2)(10)(10^{-6})(19.167)}{128} = 0.585$$

The interpolation formula of Eq. (12-16) will have to be used. From Figs. 12-16, 12-21, and 12-19

For $l/d = \infty, \quad h_o/c = 0.96, \quad P/p_{\max} = 0.84, \quad \frac{Q}{rcNl} = 3.09$

$l/d = 1, \quad h_o/c = 0.77, \quad P/p_{\max} = 0.52, \quad \frac{Q}{rcNl} = 3.6$

$l/d = \frac{1}{2}, \quad h_o/c = 0.54, \quad P/p_{\max} = 0.42, \quad \frac{Q}{rcNl} = 4.4$

$l/d = \frac{1}{4}, \quad h_o/c = 0.31, \quad P/p_{\max} = 0.28, \quad \frac{Q}{rcNl} = 5.25$

Equation (12-16) is easily programmed by code or by using a spreadsheet. The results are:

	l/d	y_{∞}	y_1	$y_{1/2}$	$y_{1/4}$	$y_{l/d}$
h_o/c	2	0.96	0.77	0.54	0.31	0.88
$P/p_{\max}$	2	0.84	0.52	0.42	0.28	0.64
$Q/rcNl$	2	3.09	3.60	4.40	5.25	3.28

$\therefore h_o = 0.88(0.001) = 0.00088 \text{ in} \quad \text{Ans.}$

$p_{\max} = \frac{128}{0.64} = 200 \text{ psi} \quad \text{Ans.}$

$Q = 3.28(0.625)(0.001)(19.167)(2.5) = 0.098 \text{ in}^3/\text{s} \quad \text{Ans.}$

12-3

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

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

$l/d = 1.5/3 = 0.5$

$r/c = 1.5/0.0025 = 600$

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

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

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

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

Figs. 12-16 and 12-21: $h_o/c = 0.11, \quad P/p_{\max} = 0.21$

$h_o = 0.11(0.0025) = 0.000275 \text{ in} \quad \text{Ans.}$

$p_{\max} = 177.78/0.21 = 847 \text{ psi} \quad \text{Ans.}$

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

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

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

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

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

12-4

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.006 - 3.000}{2} = 0.003$$

$$r \doteq 3.000/2 = 1.5 \text{ in}$$

$$l/d = 1$$

$$r/c = 1.5/0.003 = 500$$

$$N = 750/60 = 12.5 \text{ rev/s}$$

$$P = \frac{600}{3(3)} = 66.7 \text{ psi}$$

Fig. 12-14: SAE 10W, $\mu' = 2.1 \mu\text{reyn}$

$$S = (500^2) \left[\frac{2.1(10^{-6})(12.5)}{66.7} \right] = 0.0984$$

From Figs. 12-16 and 12-21:

$$h_o/c = 0.34, \quad P/p_{\max} = 0.395$$

$$h_o = 0.34(0.003) = 0.001020 \text{ in} \quad \text{Ans.}$$

$$p_{\max} = \frac{66.7}{0.395} = 169 \text{ psi} \quad \text{Ans.}$$

Fig. 12-14: SAE 20W-40, $\mu' = 5.05 \mu\text{reyn}$

$$S = (500^2) \left[\frac{5.05(10^{-6})(12.5)}{66.7} \right] = 0.237$$

From Figs. 12-16 and 12-21:

$$h_o/c = 0.57, \quad P/p_{\max} = 0.47$$

$$h_o = 0.57(0.003) = 0.00171 \text{ in} \quad \text{Ans.}$$

$$p_{\max} = \frac{66.7}{0.47} = 142 \text{ psi} \quad \text{Ans.}$$

12-5

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

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

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

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

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

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

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

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

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

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

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

The power loss due to friction is

$$H = \frac{2\pi f W r N}{778(12)} = \frac{2\pi(0.00456)(600)(1)(13.33)}{778(12)} \\ = 0.0245 \text{ Btu/s} \quad \text{Ans.}$$

$$Q = 5.3rcNl \\ = 5.3(1)(0.0012)(13.33)(1) \\ = 0.0848 \text{ in}^3/\text{s} \quad \text{Ans.}$$

12-6

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

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

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

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

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

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

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

$$h_o/c = 0.52, \quad fr/c = 4.5, \quad Q_s/Q = 0.57$$

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

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

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

The power loss due to friction is

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

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

12-7

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{30.05 - 30.00}{2} = 0.025 \text{ mm}$$

$$r = \frac{d}{2} = \frac{30}{2} = 15 \text{ mm}$$

$$\frac{r}{c} = \frac{15}{0.025} = 600$$

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

$$P = \frac{2750}{30(50)} = 1.833 \text{ MPa}$$

$$S = (600^2) \left[\frac{60(10^{-3})(18.67)}{1.833(10^6)} \right] = 0.22$$

$$\frac{l}{d} = \frac{50}{30} = 1.67$$

This l/d requires use of the interpolation of Raimondi and Boyd, Eq. (12-16).

From Fig. 12-16, the h_o/c values are:

$$y_{1/4} = 0.18, \quad y_{1/2} = 0.34, \quad y_1 = 0.54, \quad y_{\infty} = 0.89$$

Substituting into Eq. (12-16), $\frac{h_o}{c} = 0.659$

From Fig. 12-18, the fr/c values are:

$$y_{1/4} = 7.4, \quad y_{1/2} = 6.0, \quad y_1 = 5.0, \quad y_{\infty} = 4.0$$

Substituting into Eq. (12-16), $\frac{fr}{c} = 4.59$

From Fig. 12-19, the $Q/(rcNl)$ values are:

$$y_{1/4} = 5.65, \quad y_{1/2} = 5.05, \quad y_1 = 4.05, \quad y_{\infty} = 2.95$$

Substituting into Eq. (12-16), $\frac{Q}{rcNl} = 3.605$

$$h_o = 0.659(0.025) = 0.0165 \text{ mm} \quad \text{Ans.}$$

$$f = 4.59/600 = 0.00765 \quad \text{Ans.}$$

$$Q = 3.605(15)(0.025)(18.67)(50) = 1263 \text{ mm}^3/\text{s} \quad \text{Ans.}$$

12-8

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

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

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

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

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

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

Fig. 12-13: SAE 20, $\mu = 18.5 \text{ mPa} \cdot \text{s}$

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

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

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

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

$$f = 5.1/750 = 0.0068$$

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

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, $\mu = 37 \text{ MPa} \cdot \text{s}$

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

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

$$h_o/c = 0.42, \quad fr/c = 8.5, \quad P/p_{\max} = 0.38$$

$$h_o = 0.42(0.05) = 0.021 \text{ mm} \quad \text{Ans.}$$

$$f = 8.5/750 = 0.0113$$

$$T = fWr = 0.0113(2)(37.5) = 0.85 \text{ N} \cdot \text{m}$$

$$H_{\text{loss}} = 2\pi TN = 2\pi(0.85)(12) = 64 \text{ W} \quad \text{Ans.}$$

$$p_{\max} = 0.741/0.38 = 1.95 \text{ MPa} \quad \text{Ans.}$$

12-9

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{50.05 - 50}{2} = 0.025 \text{ mm}$$

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

$$r/c = 25/0.025 = 1000$$

$$l/d = 25/50 = 0.5, \quad N = 840/60 = 14 \text{ rev/s}$$

$$P = \frac{2000}{25(50)} = 1.6 \text{ MPa}$$

Fig. 12-13: SAE 30, $\mu = 34 \text{ mPa} \cdot \text{s}$

$$S = (1000^2) \left[\frac{34(10^{-3})(14)}{1.6(10^6)} \right] = 0.2975$$

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

$$h_o/c = 0.40, \quad fr/c = 7.8, \quad Q_s/Q = 0.74, \quad Q/(rcNl) = 4.9$$

$$h_o = 0.40(0.025) = 0.010 \text{ mm} \quad \text{Ans.}$$

$$f = 7.8/1000 = 0.0078$$

$$T = fWr = 0.0078(2)(25) = 0.39 \text{ N} \cdot \text{m}$$

$$H = 2\pi TN = 2\pi(0.39)(14) = 34.3 \text{ W} \quad \text{Ans.}$$

$$Q = 4.9rcNl = 4.9(25)(0.025)(14)(25) = 1072 \text{ mm}^3/\text{s}$$

$$Q_s = 0.74(1072) = 793 \text{ mm}^3/\text{s} \quad \text{Ans.}$$

12-10 Consider the bearings as specified by

$$\text{minimum } f: \quad d_{-t_d}^{+0}, \quad b_{-0}^{+t_b}$$

$$\text{maximum } W: \quad d_{-t_d}'^{+0}, \quad b_{-0}^{+t_b}$$

and differing only in d and d' .

Preliminaries:

$$l/d = 1$$

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

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

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

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

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.

$$\begin{aligned} d' - d &= b - 0.001 - (b - 0.002) \\ &= 0.001 \text{ in} \end{aligned}$$

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 30, $N = 8 \text{ rev/s}$, $T_s = 60^\circ\text{C}$, $l/d = 1$, $d = 80 \text{ mm}$, $b = 80.08 \text{ mm}$, $W = 3000 \text{ N}$

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{80.08 - 80}{2} = 0.04 \text{ mm}$$

$$r = d/2 = 80/2 = 40 \text{ mm}$$

$$\frac{r}{c} = \frac{40}{0.04} = 1000$$

$$P = \frac{3000}{80(80)} = 0.469 \text{ MPa}$$

Trial #1: From Figure 12-13 for $T = 81^\circ\text{C}$, $\mu = 12 \text{ mPa} \cdot \text{s}$

$$\Delta T = 2(81^\circ\text{C} - 60^\circ\text{C}) = 42^\circ\text{C}$$

$$S = (1000^2) \left[\frac{12(10^{-3})(8)}{0.469(10^6)} \right] = 0.2047$$

From Fig. 12-24,

$$\frac{0.120\Delta T}{P} = 0.349 + 6.009(0.2047) + 0.0475(0.2047)^2 = 1.58$$

$$\Delta T = 1.58 \left(\frac{0.469}{0.120} \right) = 6.2^\circ\text{C}$$

Discrepancy = $42^\circ\text{C} - 6.2^\circ\text{C} = 35.8^\circ\text{C}$

Trial #2: From Figure 12-13 for $T = 68^\circ\text{C}$, $\mu = 20 \text{ mPa} \cdot \text{s}$,

$$\Delta T = 2(68^\circ\text{C} - 60^\circ\text{C}) = 16^\circ\text{C}$$

$$S = 0.2047 \left(\frac{20}{12} \right) = 0.341$$

From Fig. 12-24,

$$\frac{0.120\Delta T}{P} = 0.349 + 6.009(0.341) + 0.0475(0.341)^2 = 2.4$$

$$\Delta T = 2.4 \left(\frac{0.469}{0.120} \right) = 9.4^\circ\text{C}$$

Discrepancy = $16^\circ\text{C} - 9.4^\circ\text{C} = 6.6^\circ\text{C}$

Trial #3: $\mu = 21 \text{ mPa} \cdot \text{s}$, $T = 65^\circ\text{C}$

$$\Delta T = 2(65^\circ\text{C} - 60^\circ\text{C}) = 10^\circ\text{C}$$

$$S = 0.2047 \left(\frac{21}{12} \right) = 0.358$$

From Fig. 12-24,

$$\frac{0.120\Delta T}{P} = 0.349 + 6.009(0.358) + 0.0475(0.358)^2 = 2.5$$

$$\Delta T = 2.5 \left(\frac{0.469}{0.120} \right) = 9.8^\circ\text{C}$$

$$\text{Discrepancy} = 10^\circ\text{C} - 9.8^\circ\text{C} = 0.2^\circ\text{C} \quad O.K.$$

$$T_{av} = 65^\circ\text{C} \quad \text{Ans.}$$

$$T_1 = T_{av} - \Delta T/2 = 65^\circ\text{C} - (10^\circ\text{C}/2) = 60^\circ\text{C}$$

$$T_2 = T_{av} + \Delta T/2 = 65^\circ\text{C} + (10^\circ\text{C}/2) = 70^\circ\text{C}$$

$$S = 0.358$$

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

$$\frac{h_o}{c} = 0.68, \quad fr/c = 7.5, \quad \frac{Q}{rcNl} = 3.8, \quad \frac{Q_s}{Q} = 0.44$$

$$h_o = 0.68(0.04) = 0.0272 \text{ mm} \quad \text{Ans.}$$

$$f = \frac{7.5}{1000} = 0.0075$$

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

$$H = 2\pi TN = 2\pi(0.9)(8) = 45.2 \text{ W} \quad \text{Ans.}$$

$$Q = 3.8(40)(0.04)(8)(80) = 3891 \text{ mm}^3/\text{s}$$

$$Q_s = 0.44(3891) = 1712 \text{ mm}^3/\text{s} \quad \text{Ans.}$$

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

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

T_f	μ'	S	ΔT (From Fig. 12-24)
150	2.421	0.0921	18.5

$$T_{av} = T_s + \frac{\Delta T}{2} = 110^\circ\text{F} + \frac{18.5^\circ\text{F}}{2} = 119.3^\circ\text{F}$$

$$T_f - T_{av} = 150^\circ\text{F} - 119.3^\circ\text{F}$$

which is not 0.1 or less, therefore try averaging

$$(T_f)_{\text{new}} = \frac{150^\circ\text{F} + 119.3^\circ\text{F}}{2} = 134.6^\circ\text{F}$$

Proceed with additional trials

Trial T_f	μ'	S	ΔT	T_{av}	New T_f
150.0	2.421	0.0921	18.5	119.3	134.6
134.6	3.453	0.1310	23.1	121.5	128.1
128.1	4.070	0.1550	25.8	122.9	125.5
125.5	4.255	0.1650	27.0	123.5	124.5
124.5	4.471	0.1700	27.5	123.8	124.1
124.1	4.515	0.1710	27.7	123.9	124.0
124.0	4.532	0.1720	27.8	123.7	123.9

Note that the convergence begins rapidly. There are ways to speed this, but at this point they would only add complexity. Depending where you stop, you can enter the analysis.

(a) $\mu = 4.541(10^{-6})$ reyn, $S = 0.1724$

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

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

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

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

(d) $T = fWr = 0.00656(1200)(1.25) = 9.84$ lbf · in

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

(e) From Fig. 12-19: $\frac{Q}{rcNl} = 4.16$, $Q = 4.16(1.25)(0.002) \left(\frac{1120}{60} \right) (2.5)$
 $= 0.485 \text{ in}^3/\text{s}$ Ans.

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

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

$$\phi_{p_{\max}} = 16^\circ \text{ Ans.}$$

(g) $\phi_{p_0} = 82^\circ$ Ans.

(h) $T_f = 123.9^\circ\text{F}$ Ans.

(i) $T_s + \Delta T = 110^\circ\text{F} + 27.8^\circ\text{F} = 137.8^\circ\text{F}$ 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 $T_s = 120^\circ\text{F}$.

Below is a partial tabular summary for comparison purposes.

	$c_{\min}$ 0.001 in	$\bar{c}$ 0.002 in	$c_{\max}$ 0.003 in
T_f	132.2	125.8	124.0
ΔT	24.3	11.5	7.96
$T_{\max}$	144.3	131.5	128.0
μ'	2.587	3.014	3.150
S	0.184	0.053 7	0.024 9
ϵ	0.499	0.775 0	0.873
$\frac{fr}{c}$	4.317	1.881	1.243
$\frac{Q}{rcN_jl}$	4.129	4.572	4.691
$\frac{Q_s}{Q}$	0.582	0.824	0.903
$\frac{h_o}{c}$	0.501	0.225	0.127
f	0.006 9	0.006	0.005 9
Q	0.094 1	0.208	0.321
Q_s	0.054 8	0.172	0.290
h_o	0.000 501	0.000 495	0.000 382

Note the variations on each line. There is *not* a bearing, but an ensemble of many bearings, due to the random assembly of toleranced bushings and journals. Fortunately the distribution is bounded; the extreme cases, $c_{\min}$ and $c_{\max}$, coupled with $\bar{c}$ provide the characteristic description for the designer. All assemblies must be satisfactory.

The designer does not specify a journal-bushing bearing, but an ensemble of bearings.

12-14 Computer programs will vary—Fortran based, MATLAB, spreadsheet, etc.

12-15 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.

The task is to iteratively find the average film temperature, T_f , which makes H_{gen} and H_{loss} equal. The steps for determining $c_{\min}$ are provided within Trial #1 through Trial #3 on the following page.

Trial #1:

- Choose a value of T_f .
- Find the corresponding viscosity.
- Find the Sommerfeld number.
- Find fr/c , then

$$H_{\text{gen}} = \frac{2545}{1050} W N c \left(\frac{fr}{c} \right)$$

- Find $Q/(rcNl)$ and Q_s/Q . From Eq. (12-15)

$$\Delta T = \frac{0.103 P (fr/c)}{(1 - 0.5 Q_s/Q) [Q/(rcNl)]}$$

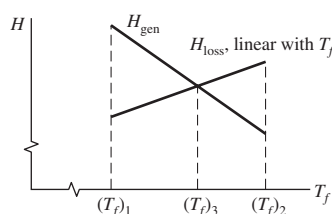
$$H_{\text{loss}} = \frac{h_{\text{CR}} A (T_f - T_{\infty})}{1 + \alpha}$$

- Display T_f , S , H_{gen} , H_{loss}

Trial #2: Choose another T_f , repeating above drill.

Trial #3:

Plot the results of the first two trials.



Choose $(T_f)_3$ from plot. Repeat the drill. Plot the results of Trial #3 on the above graph. If you are not within 0.1°F , iterate again. Otherwise, stop, and find all the properties of the bearing for the first clearance, c_{min} . See if Trumpler conditions are satisfied, and if so, analyze $\bar{c}$ and c_{max} .

The bearing ensemble in the current problem statement meets Trumpler's criteria (for $n_d = 2$).

This adequacy assessment protocol can be used as a design tool by giving the students additional possible bushing sizes.

b (in)	t_b (in)
2.254	0.004
2.004	0.004
1.753	0.003

Otherwise, the design option includes reducing l/d to save on the cost of journal machining and vendor-supplied bushings.

12-16 Continue to build a skill with pressure-fed bearings, that of finding the average temperature of the fluid film. First examine the case for $c = c_{\min}$

Trial #1:

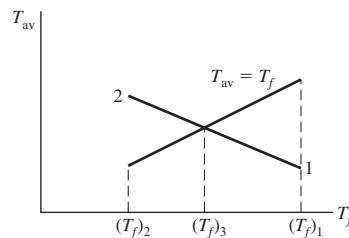
- Choose an initial T_f .
- Find the viscosity.
- Find the Sommerfeld number.
- Find fr/c , h_o/c , and ϵ .
- From Eq. (12-24), find ΔT .

$$T_{av} = T_s + \frac{\Delta T}{2}$$

- Display T_f , S , ΔT , and T_{av} .

Trial #2:

- Choose another T_f . Repeat the drill, and display the second set of values for T_f , S , ΔT , and T_{av} .
- Plot T_{av} vs T_f :



Trial #3:

Pick the third T_f from the plot and repeat the procedure. If $(T_f)_3$ and $(T_{av})_3$ differ by more than 0.1°F , plot the results for Trials #2 and #3 and try again. If they are within 0.1°F , determine the bearing parameters, check the Trumpler criteria, and compare H_{loss} with the lubricant's cooling capacity.

Repeat the entire procedure for $c = c_{\max}$ to assess the cooling capacity for the maximum radial clearance. Finally, examine $c = \bar{c}$ to characterize the ensemble of bearings.

12-17 An adequacy assessment associated with a design task is required. Trumpler's criteria will do.

$$d = 50.00_{-0.05}^{+0.00} \text{ mm}, \quad b = 50.084_{-0.000}^{+0.010} \text{ mm}$$

$$\text{SAE 30}, N = 2880 \text{ rev/min or } 48 \text{ rev/s}, \quad W = 10 \text{ kN}$$

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

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

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

$$l' = \frac{1}{2}(55 - 5) = 25 \text{ mm}$$

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

$$p = \frac{W}{4rl'} = \frac{10(10^6)}{4(0.25)(0.25)} = 4000 \text{ kPa}$$

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

$$S = (595^2) \left[\frac{13(10^{-3})(48)}{4000(10^3)} \right] = 0.055$$

From Figs. 12-18 and 12-16: $\frac{fr}{c} = 2.3, \quad \epsilon = 0.85.$

$$\begin{aligned} \text{From Eq. (12-25), } \Delta T &= \frac{978(10^6)}{1 + 1.5\epsilon^2} \frac{(fr/c)SW^2}{p_s r^4} \\ &= \frac{978(10^6)}{1 + 1.5(0.85)^2} \left[\frac{2.3(0.055)(10^2)}{200(25)^4} \right] \\ &= 76.0^\circ\text{C} \end{aligned}$$

$$T_{av} = T_s + \Delta T/2 = 55^\circ\text{C} + (76^\circ\text{C}/2) = 93^\circ\text{C}$$

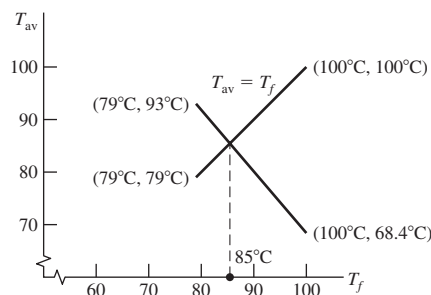
Trial #2: Choose $(T_f)_2 = 100^\circ\text{C}$. From Fig. 12-13, $\mu = 7 \text{ mPa} \cdot \text{s}$.

$$S = 0.055 \left(\frac{7}{13} \right) = 0.0296$$

From Figs. 12-18 and 12-16: $\frac{fr}{c} = 1.6, \quad \epsilon = 0.90$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.9)^2} \left[\frac{1.6(0.0296)(10^2)}{200(25)^4} \right] = 26.8^\circ\text{C}$$

$$T_{av} = 55^\circ\text{C} + \frac{26.8^\circ\text{C}}{2} = 68.4^\circ\text{C}$$



Trial #3: Thus, the plot gives $(T_f)_3 = 85^\circ\text{C}$. From Fig. 12-13, $\mu = 10.8 \text{ mPa} \cdot \text{s}$.

$$S = 0.055 \left(\frac{10.8}{13} \right) = 0.0457$$

From Figs. 12-18 and 12-16: $\frac{fr}{c} = 2.2, \quad \epsilon = 0.875$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.875^2)} \left[\frac{2.2(0.0457)(10^2)}{200(25)^4} \right] = 58.6^\circ\text{C}$$

$$T_{av} = 55^\circ\text{C} + \frac{58.6^\circ\text{C}}{2} = 84.3^\circ\text{C}$$

Result is close. Choose $\bar{T}_f = \frac{85^\circ\text{C} + 84.3^\circ\text{C}}{2} = 84.7^\circ\text{C}$

Fig. 12-13:

$$\mu = 10.8 \text{ MPa} \cdot \text{s}$$

$$S = 0.055 \left(\frac{10.8}{13} \right) = 0.0457$$

$$\frac{fr}{c} = 2.23, \quad \epsilon = 0.874, \quad \frac{h_o}{c} = 0.13$$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.874^2)} \left[\frac{2.23(0.0457)(10^2)}{200(25^4)} \right] = 59.5^\circ\text{C}$$

$$T_{av} = 55^\circ\text{C} + \frac{59.5^\circ\text{C}}{2} = 84.7^\circ\text{C} \quad O.K.$$

From Eq. (12-22)

$$\begin{aligned} Q_s &= (1 + 1.5\epsilon^2) \frac{\pi p_s r c^3}{3\mu l'} \\ &= [1 + 1.5(0.874^2)] \left[\frac{\pi(200)(0.042^3)(25)}{3(10)(10^{-6})(25)} \right] \\ &= 3334 \text{ mm}^3/\text{s} \end{aligned}$$

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

Trumpler:

$$\begin{aligned} h_o &= 0.0002 + 0.00004(50/25.4) \\ &= 0.000279 \text{ in} \quad \text{Not } O.K. \end{aligned}$$

$$T_{\max} = T_s + \Delta T = 55^\circ\text{C} + 63.7^\circ\text{C} = 118.7^\circ\text{C} \quad \text{or} \quad 245.7^\circ\text{F} \quad O.K.$$

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

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

There is no point in proceeding further.

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

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.

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

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

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

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 $d = 2.000$ 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: $\epsilon = 0.7$, $fr/c = 5.5$

Eq. (12-24):

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

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

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}	$T_{\max}$	fos	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.

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

The ensemble median assembly has $\text{fom} = -9.31$.

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 $c = 0.003$ the constraints are "loose." Set

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

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

For the ensemble

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

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

At $c_{\min} = 0.003$ in: $\bar{T}_f = 138.4^\circ\text{F}$, $\mu' = 3.160$, $S = 0.0297$, $H_{\text{loss}} = 1035$ 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, $\text{fom} = -9.246$ and the Trumpler conditions are *O.K.*

At $c_{\max} = 0.005$ in: $\bar{T}_f = 125.68^\circ\text{F}$, $\mu' = 4.325 \mu\text{reyn}$, $S = 0.01466$, $H_{\text{loss}} = 1129$ 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 From Table 12-1, Seireg and Dandage, $\mu_0 = 0.0141(10^6)$ reyn and $b = 1360.0$

$$\mu(\mu\text{reyn}) = 0.0141 \exp[1360/(T + 95)] \quad (T \text{ in } ^\circ\text{F})$$

$$= 0.0141 \exp[1360/(1.8C + 127)] \quad (C \text{ in } ^\circ\text{C})$$

$$\mu(\text{mPa} \cdot \text{s}) = 6.89(0.0141) \exp[1360/(1.8C + 127)] \quad (C \text{ in } ^\circ\text{C})$$

For SAE 30 at 79°C

$$\mu = 6.89(0.0141) \exp\{1360/[1.8(79) + 127]\}$$

$$= 15.2 \text{ mPa} \cdot \text{s} \quad \text{Ans.}$$

12-21 Originally

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

Doubled,

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

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	$\bar{T}_f$	fr/c	Q_s	h_o/c	ϵ	H_{loss}	h_o	Trumpler h_o	f
(a)	0.007	3.416	0.0310	135.1	0.1612	6.56	0.1032	0.897	9898	0.000722	0.000360	0.00567
(b)	0.0035	3.416	0.0310	135.1	0.1612	0.870	0.1032	0.897	1237	0.000361	0.000280	0.00567

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_o is related by a 2-fold increase. Trumpler's $(h_o)_{\text{min}}$ is related by a 1.286-fold increase

$$\left. \begin{array}{ll} \text{fom} = -82.37 & \text{for double size} \\ \text{fom} = -10.297 & \text{for original size} \end{array} \right\} \text{an 8-fold increase for double-size}$$

12-22 From Table 12-8: $K = 0.6(10^{-10}) \text{ in}^3 \cdot \text{min}/(\text{lbf} \cdot \text{ft} \cdot \text{h})$. $P = 500/[(1)(1)] = 500 \text{ psi}$,
 $V = \pi DN/12 = \pi(1)(200)/12 = 52.4 \text{ ft/min}$

Tables 12-10 and 12-11: $f_1 = 1.8$, $f_2 = 1$

Table 12-12: $PV_{\text{max}} = 46700 \text{ psi} \cdot \text{ft/min}$, $P_{\text{max}} = 3560 \text{ psi}$, $V_{\text{max}} = 100 \text{ ft/min}$

$$P_{\text{max}} = \frac{4}{\pi} \frac{F}{DL} = \frac{4(500)}{\pi(1)(1)} = 637 \text{ psi} < 3560 \text{ psi} \quad O.K.$$

$$P = \frac{F}{DL} = 500 \text{ psi} \quad V = 52.4 \text{ ft/min}$$

$$PV = 500(52.4) = 26200 \text{ psi} \cdot \text{ft/min} < 46700 \text{ psi} \cdot \text{ft/min} \quad O.K.$$

Solving Eq. (12-32) for t

$$t = \frac{\pi D L w}{4 f_1 f_2 K V F} = \frac{\pi(1)(1)(0.005)}{4(1.8)(1)(0.6)(10^{-10})(52.4)(500)} = 1388 \text{ h} = 83\,270 \text{ min}$$

$$\text{Cycles} = Nt = 200(83\,270) = 16.7 \text{ rev} \quad \text{Ans.}$$

12-23 Estimate bushing length with $f_1 = f_2 = 1$, and $K = 0.6(10^{-10}) \text{ in}^3 \cdot \text{min}/(\text{lbf} \cdot \text{ft} \cdot \text{h})$

$$\text{Eq. (12-32):} \quad L = \frac{1(1)(0.6)(10^{-10})(2)(100)(400)(1000)}{3(0.002)} = 0.80 \text{ in}$$

From Eq. (12-38), with $f_s = 0.03$ from Table 12-9 applying $n_d = 2$ to F
and $h_{CR} = 2.7 \text{ Btu}/(\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})$

$$L \doteq \frac{720(0.03)(2)(100)(400)}{778(2.7)(300 - 70)} = 3.58 \text{ in}$$

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

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

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

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

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

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

$$P_{\max} = \frac{4(2)(100)}{\pi(7/8)(1)} = 291 \text{ psi} < 3560 \text{ psi} \quad \text{O.K.}$$

$$P = \frac{2(100)}{7/8(1)} = 229 \text{ psi}$$

$$V = \frac{\pi(7/8)(400)}{12} = 91.6 \text{ ft/min} < 100 \text{ ft/min} \quad \text{O.K.}$$

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

V	f_1
33	1.3
91.6	f_1
100	1.8

$$\Rightarrow f_1 = 1.3 + (1.8 - 1.3) \left(\frac{91.6 - 33}{100 - 33} \right) = 1.74$$

$$L = 0.80(1.74) = 1.39 \text{ in}$$

Trial 3: Try $D = 7/8$ in, $L = 1.5$ in

$$P_{\max} = \frac{4(2)(100)}{\pi(7/8)(1.5)} = 194 \text{ psi} < 3560 \text{ psi} \quad O.K.$$

$$P = \frac{2(100)}{7/8(1.5)} = 152 \text{ psi}, \quad V = 91.6 \text{ ft/min}$$

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

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

Suggestion: Try smaller sizes.