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Problem Solutions

Flack

Chapter 1

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101

$$F = \dot{m}(u_e - u_a) + A_e(p_e - p_a)$$

$$A_e = \pi D_e^2 / 4 = \pi 29^2 / 4 = 660.5 \text{ m}^2$$

$$F = \frac{175}{32.17} \frac{\text{sl}}{\text{sec}} (2437 - 728) \frac{\text{ft}}{\text{s}} + 660.5 (6.75 - 14.69) \text{ m}^2 \frac{\text{lb}_f}{\text{m}^2}$$

$$= \frac{9297}{\text{mom}} - \frac{5244}{\text{pressure}}$$

$$F = 4052 \text{ lb}_f$$

1.2

$$F = \dot{m} (u_e - u_a) + A_e (p_e - p_a)$$

$$A_e = \pi D_e^2 / 4 = \pi 29^2 / 4 = 660.5 \text{ m}^2$$

$$F = \frac{175}{32.17} \frac{\text{N}}{\text{sec}} (2437 - 728) \frac{\text{ft}}{\text{s}} + 660.5 (6.75 - 676) \text{ m}^2 \frac{\text{lbf}}{\text{m}^2}$$

$$= \frac{9297}{\text{mom}} - \frac{7}{\text{pressure}}$$

$$F = 9290 \text{ lbf}$$

1.3 Turbofan

$$\dot{m}_e = 150 \text{ lbm/s}$$

$$v_a = 893 \text{ ft/s}$$

$$\dot{m}_s = 2.2 \times 150 \text{ lbm/s} = 330 \text{ lbm/s}$$

$$A_f = 336 \text{ in}^2$$

$$p_f = 14.7 \text{ psia}$$

$$v_f = 2288 \text{ ft/s}$$

$$A_c = 542 \text{ in}^2$$

$$p_c = 15.8 \text{ psia}$$

$$v_c = 1164 \text{ ft/s}$$

$$F = A_c (p_c - p_a) + A_f (p_f - p_a) + \dot{m}_c (v_c - v_a) + \dot{m}_s (v_s - v_a)$$

$$= 542 (15.8 - 14.7) + 336 (14.7 - 14.7)$$

$$+ 150 (1164 - 893) \frac{\text{lbm}}{\text{s}} \frac{\text{sl}}{32.2 \text{ lbm}} \frac{\text{ft}}{\text{s}}$$

$$+ 330 (2288 - 893) / 32.2$$

$$= 596 \text{ lbf} + 0 + 1262 \text{ lbf} + 14297 \text{ lbf}$$

$$\boxed{F = 16155 \text{ lbf}}$$

- core - + - - - - -
fan

$$F_c = 1858 \Rightarrow 11.5\%$$

$$F_f = 14297 \Rightarrow 88.5\%$$

Fully Mixed Turbofan

1.4

$$p_a = 14.69 \text{ psia}$$

$$A_c = 851 \text{ in}^2$$

$$u_a = 893 \text{ ft/s}$$

$$p_e = 18.4 \text{ psia}$$

$$\dot{m} = 150 \text{ lbm/s core}$$

$$u_e = 1435 \text{ ft/s}$$

$$\lambda = 2.2 \text{ BPRatio}$$

$$\dot{m}_f \text{ negligible}$$

$$F = A_e (p_e - p_a) + \dot{m}_e (u_e - u_a)$$

$$\dot{m}_e = \dot{m} + 2.2 \dot{m} = 3.2 \dot{m}$$

$$F = 851 (18.4 - 14.69) \frac{\text{lb}}{\text{in}^2} \text{ in}^2 + 3.2 \times 150 \frac{\text{lbm}}{\text{s}} (1435 - 893) \frac{\text{ft}}{\text{s}}$$

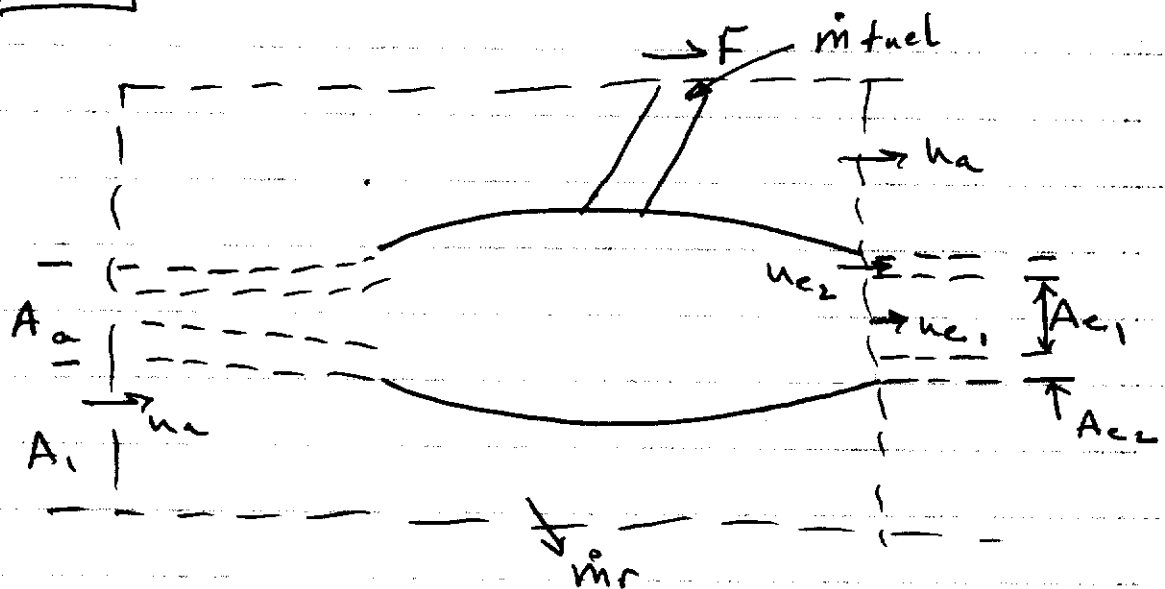
$$32.17 \frac{\text{lbm} \cdot \text{ft}}{\text{s}^2 \text{ lbf}}$$

$$F = 11237 \text{ lbf}$$

$$\begin{aligned}
 \boxed{1.5} \quad F &= \dot{m}(u_B - u_a) + A(p_B - p_a) + \overline{F_p} \\
 &= 30 \frac{(625 - 783)}{32.17} + 290(14.7 - 14.7) + 2517 \\
 &= -147 + 2517
 \end{aligned}$$

$$\boxed{F = 2370 \text{ lbf}}$$

1.6 Mixed Turbofan



x Momentum:

$$F + p_a A_a + p_a A_b - p_{e1} A_{e1} - p_{e2} A_{e2} - p_a A_e + F_{bx} =$$

$$- u_a p_a A_a u_a + u_{e1} p_{e1} A_{e1} u_{e1} + u_{e2} p_{e2} A_{e2} u_{e2}$$

$$- u_b p_a A_b u_b + u_a p_a A_e u_a - \dot{m}_f u_{fx} + \dot{m}_f u_a$$

now if the exhaust is fully mixed

$$u_{e1} = u_{e2} = u_e$$

$$p_{e1} = p_{e2} = p_e$$

$$p_{e2} = p_{e1} = p_e$$

$$\text{Also } A_e = A_{e1} + A_{e2}$$

so above becomes with no body force

$$F + p_a A_e + p_a - p_e A_e - p_a A_e + F_{bx} =$$

$$- u_a p_a A_a u_a + u_e p_e A_e u_e - u_b p_a A_b u_b + u_a p_a A_e u_a + \dot{m}_f u_a - \dot{m}_f u_{fx}$$

This is the same as eq. 1.F.2 (exactly)!

One can proceed exactly as in Text.

11.7 Exhausted Fan $u_a = Ma \sqrt{\gamma R T_a} = 748$
 $p_a = 4.36 \text{ psia @ } 30000 \text{ ft}$

(a) $\dot{m}_{\text{fuel}}$ small

$$F = \dot{m}_B (u_B - u_a) + A_B (p_B - p_a) + \dot{m}_S (u_S - u_a) + A_S (p_S - p_a)$$

$$= \frac{190}{32.17} (1880 - 748) + 901 (9.42 - 4.36) + 1.2 \times \frac{190}{32.17} (1350 - 748) + 936 (4.36 - 4.36)$$

$$= 6686 + 4561 + 4267 + 0$$

$$= \frac{11247}{\text{core}} + \frac{4267}{\text{Fan}}$$

$$= 15514 \text{ lbf}$$

$\approx$

(b) $\dot{m}_{\text{fuel}}$ not small

$$F = \dot{m}_B u_B - \dot{m}_a u_a + A_B (p_B - p_a) + \dot{m}_S (u_S - u_a) + A_S (p_S - p_a)$$

$$= \left(\frac{190 + 4.66}{32.17} \right) (1880) - \frac{190}{32.17} (748) + 901 (9.42 - 4.36)$$

$$+ 1.2 \times \frac{190}{32.2} (1350 - 748) + 936 (4.36 - 4.36)$$

$$= 6955 + 4561 + 4267 + 0$$

$$= \frac{11516}{\text{core}} + \frac{4267}{\text{Fan}} = 15783 \text{ lbf}$$

1.7 cont

or.

$$F = \dot{m}_e(u_e - u_a) + \dot{m}_s(u_s - u_a) + \dot{m}_f(u_a) + A_e(p_e - p_a) + A_s(p_s - p_a)$$

$$= \frac{(190 + 4.66)}{32.17} (1880 - 748) + \frac{1.2 \times 190}{32.2} (1350 - 748)$$

$$+ \frac{4.66}{32.17} \times 748 + 901(9.42 - 4.36) + 936(4.36 - 4.31)$$

$$= 15783$$

1.8

$$18000 \text{ ft} \quad M=0.8 \quad A_e=361 \text{ m}^2 \quad p_e=22.4 \text{ psia}$$

$$V_e=1938 \quad F=11666 \text{ lbf} \quad \dot{m}_f=4.04 \frac{\text{lb}_m}{\text{s}}$$

$$\dot{m}=? \quad (\text{a}) \dot{m}_f \ll \dot{m} \quad (\text{b}) \dot{m}_f \text{ included.}$$

$$F = \dot{m}_f u_a + \dot{m}_e (u_e - u_a) + A_e (p_e - p_a) - \dot{m}_f u_{fx}$$

$$(\text{a}) \quad F = \dot{m} (u_e - u_a) + A_e (p_e - p_a)$$

$$18000 \text{ ft} \Rightarrow T_a = 454.6 \text{ R} \quad p_a = 7.347$$

$$a_a = \sqrt{\gamma R T} = 1045 \text{ ft/s}$$

$$u_a = M_a a_a = 836.1$$

$$11666 = \frac{\dot{m} (1938 - 836.1)}{32.17} + 361 (22.4 - 7.35)$$

$$\boxed{\dot{m} = 181.9 \text{ lb}_m/\text{s}}$$

(b)

$$11666 = \frac{4.04 (836.1)}{32.17} + \frac{\dot{m}_e (1938 - 836.1)}{32.17} + 361 (22.4 - 7.35)$$

$$\dot{m}_e = 178.9 = \dot{m} + \dot{m}_f$$

$$\boxed{\dot{m} = 174.8 \text{ lb}_m/\text{s}}$$

1.9 Turbofan 24000 ft $p_a = 5.69 \text{ psia}$
 $M_a = 0.70$ $T_a = 433.1 \text{ R}$
 $\alpha = 3.0$ $u_a = M_a \sqrt{\gamma R T_a} = 716 \text{ ft/s}$

$$\dot{m}_{\text{fuel}} = 3.77 \text{ lbm/s}$$

$$A_{\text{fan exit}} = 1259 \text{ m}^2$$

$$A_{\text{core exit}} = 1302 \text{ m}^2$$

$$\text{Fan exit } V_{el} = 1146 \text{ ft/s}$$

$$\text{Core exit } V_{el} = 1489 \text{ ft/s}$$

$$\text{Thrust } F = 15536 \text{ lbf}$$

$$p_c = 5.69 \text{ psia (core)}$$

$$p_s = 9.74 \text{ psia (fan)}$$

$$(a) F = A_c(p_c - p_a) + A_s(p_s - p_a) + \dot{m}_e(u_e - u_a) + \dot{m}_s(u_s - u_a)$$

$$\text{ignoring } \dot{m}_f \quad \dot{m}_e = \dot{m}_{\text{core}} = \dot{m}$$

$$\dot{m}_s = \alpha \dot{m} = 3\dot{m}$$

$$F = A_c(p_c - p_a) + A_s(p_s - p_a) = \dot{m}(u_e - u_a) + 3\dot{m}(u_s - u_a)$$

$$\dot{m} = \frac{F - A_c(p_c - p_a) - A_s(p_s - p_a)}{u_e + 3u_s - 4u_a}$$

$$= \frac{15536 - 1302(5.69 - 5.69) - 1259(9.74 - 5.69)}{1489 + 3 \times 1146 - 4 \times 716} \times 32.17$$

$$\boxed{\dot{m} = 162.9 \text{ lbm/s}}$$

(b) include $\dot{m}_f$

$$F = A_e(p_e - p_a) + A_s(p_s - p_a) + \dot{m}_e(u_e - u_a) + \dot{m}_s(u_s - u_a) + \dot{m}_f u_a$$

$$\dot{m}_e = \dot{m} + \dot{m}_f$$

$$\dot{m}_s = 2\dot{m} = 3\dot{m}$$

$$\dot{m} = \frac{F - A_e(p_e - p_a) - A_s(p_s - p_a) - \dot{m}_f u_a}{u_e + 3u_s - 4u_a}$$

$$= \frac{15536 - 1302(5.69 - 5.69) - 1259(9.74 - 5.69) - \frac{3.77 \times 1489}{3.22}}{1489 + 3(1146) - 4 \times 7.16}$$

$$= \frac{15536 - 1259(4.05) - 3.77 \times 464.28}{1489 + 3338 - 28.64}$$

$$= 32.17$$

$$\boxed{\dot{m} = 160.18 \frac{\text{lbm}}{\text{s}}}$$

$$\dot{m}_e = 160.18 + 3.77$$

$$\boxed{\dot{m}_e = 163.95 \text{ lbm/s}}$$

1.10

Turbo prop

$$9000 \text{ ft alt} \Rightarrow p_a = 10.5 \text{ psia} \quad p_e = 10.5 \text{ psia}$$

$$V_a = 487 \text{ ft/s} \quad V_e = 1137 \text{ ft/s}$$

$$\rho_e = 0.000453 \text{ sl/ft}^3 \quad \dot{m}_{\text{fuel}} = 0.95 \text{ lbm/s}$$

$$F_{\text{prop}} = 4243 \text{ lbf} \quad F_{\text{tot}} = 4883 \text{ lbf}$$

$$\dot{m}_a = \dot{m}_e - \dot{m}_f = \rho_e V_e A_e - \dot{m}_f$$

$$F_{\text{tot}} = F_{\text{prop}} + F_{\text{core}}$$

$$F_{\text{core}} = F_{\text{tot}} - F_{\text{prop}} = 4883 - 4243 = 640 \text{ lbf}$$

$$F_{\text{core}} = \dot{m}_f V_a + \dot{m}_e (u_e - u_a) + A_e (p_e - p_a)$$

$$A_e \rho_e u_e (u_e - u_a) = F - \dot{m}_f u_a$$

$$= 640 - 0.95 \frac{\text{lbm}}{\text{s}} \cdot 487 \frac{\text{ft}}{\text{s}} / 32.2 \frac{\text{lbm}}{\text{s}}$$

$$= 625.6 \text{ lbf}$$

$$\text{so } A_e = \frac{625.6 \text{ lbf}}{0.000453 \frac{\text{sl}}{\text{ft}^3} \cdot 1137 \frac{\text{ft}}{\text{s}} (1137 - 487) \frac{\text{ft}}{\text{s}}}$$

$$= 1.869 \text{ ft}^2$$

$$\text{if Round } A_e = \pi \frac{D^2}{4} \Rightarrow \boxed{D = 1.54 \text{ ft}}$$

$$\dot{m}_a = \dot{m}_e - \dot{m}_f = \rho_e u_e A_e - \dot{m}_f$$

$$= 0.000453 \frac{\text{sl}}{\text{ft}^3} \cdot 1137 \frac{\text{ft}}{\text{s}} \cdot 1.87 \text{ ft}^2 \cdot 32.2 \frac{\text{lbm}}{\text{s}} - 0.95 \frac{\text{lbm}}{\text{s}}$$

$$\boxed{\dot{m}_a = 30.1 \text{ lbm/s}}$$

1.11 Turbo jet @ 20000 ft @ $M = 0.75$

$$p_a = 6.75 \text{ psia} \quad T_a = 447.4^\circ\text{R} \quad \gamma = 1.40$$

$$p_{\text{exit}} = 19.7 \text{ psia}$$

$$u_{\text{exit}} = 1965 \text{ ft/s}$$

$$\rho_{\text{exit}} = 0.000979 \text{ sl/ft}^3$$

$$\dot{m}_f = 3.16 \text{ lbm/s}$$

$$F = 8995 \text{ lbf}$$

$$u_a = 0.75 \sqrt{\gamma R T_a} = 779.5 \text{ ft/s}$$

(a) Find injected mass flow rate

$$F = \dot{m}_f u_a + \dot{m}_c (u_e - u_a) + A_e (p_e - p_a)$$

$$A_e = \dot{m}_e / \rho_e u_e \quad \dot{m}_{\text{core}} = \dot{m}_e - \dot{m}_f$$

$$F = \dot{m}_f u_a + \dot{m}_c (u_e - u_a) + \dot{m}_c (p_e - p_a) / \rho_e u_e$$

$$\dot{m}_c = [F - \dot{m}_f u_a] / \left[(u_e - u_a) + \frac{p_e - p_a}{\rho_e u_e} \right]$$

$$= \frac{(8995)(32.2) - (3.16)(779.5)}{(1965 - 779.5) + \frac{144(19.7 - 6.75)}{(0.000979)(1965)}}$$

$$= 133.27 \text{ lbm/s}$$

$$\therefore \dot{m}_{\text{core}} = 133.27 - 3.16 = \boxed{130.1 \text{ lbm/s}}$$

$$\$ \quad TSFC = \frac{\dot{m}_f}{F} = \frac{3.16 \times 3600}{8995}$$

$$= \boxed{1.26 \frac{\text{lb}_m}{\text{hr lb}_f}}$$

(b) Find Diameter

$$A_c = \frac{\pi}{4} D_c^2 = \frac{\dot{m}_c}{\rho_c u_c}$$

$$D_c = \sqrt{\frac{4 \dot{m}_c}{\pi \rho_c u_c}}$$

$$= \sqrt{\frac{(4)(133.27)}{(3.1416)(0.000979)(1965)(32.2)}}$$

$$= \boxed{1.655 \text{ ft}} \quad \text{or} \quad 19.9 \text{ in}$$

$$\boxed{11.12} \quad 50000 \text{ ft} \Rightarrow p_a = 1.69 \text{ } \gamma \text{sia}$$

$$T_a = 390.0 \text{ } ^\circ \text{R}$$

$$a_a = \sqrt{\gamma R T} = \sqrt{(1.4)(53.35)(32.17)(390)} = 968 \text{ ft/sec}$$

$$u_a = M_a a_a = 3872 \text{ ft/sec}$$

$$A_e = \frac{\pi D_e^2}{4} = 789 \text{ m}^2$$

$$\dot{m}_e = \dot{m} + \dot{m}_f = 9013.74 = 937$$

$$F = \dot{m}_f u_a + \dot{m}_e (u_e - u_a) + A_e (p_e - p_a)$$

$$= \frac{3.74}{32.17} (3872) + \frac{937}{32.17} (5726 - 3872) + 789 (1.60 - 1.69)$$

$$= 450 + 5402 - 71 = \boxed{5781 \text{ lbf}}$$

$$\text{TSFC} = \frac{3.74 \times 3600}{5781} = \boxed{2.33 \frac{\text{lbm}}{\text{hr lbf}}}$$

$$\boxed{10.13} \quad F = A_c (p_c - p_a) + A_f (p_f - p_a) + \dot{m}_c (u_c - u_a) + \dot{m}_f (u_f - u_a) + \dot{m}_f u_a$$

$$25000 \text{ ft} \Rightarrow T_c = 429.6^\circ \text{R} \quad p_c = 5.46 \text{ psia}$$

$$a_c = \sqrt{\gamma R T_c} = 1016 \text{ ft/sec}$$

$$\dot{m}_{sc} = \rho_{sc} u_s A_f \quad \dot{m}_c = \rho_c u_c A_c \quad A_c = \dot{m}_c / \rho_c u_c \text{ etc.}$$

$$f = \text{fuel ratio} = \dot{m}_f / \dot{m}$$

$$\dot{m}_c = \dot{m} + \dot{m}_f = \dot{m} (1 + f)$$

(a)

$$F = \frac{\dot{m}(1+f)}{\rho_c u_c} (p_c - p_a) + \frac{\dot{m} f}{\rho_{sc} A_f} (p_f - p_a) + \dot{m}(1+f) (u_c - u_a) + \dot{m} f u_a$$

$$\frac{10580 \text{ ft}}{\text{sec}} = \dot{m} \left[\frac{1.0255 (10.26 - 5.46)}{0.000578 \cdot 1852} + \frac{1.2 (10.07 - 5.46)}{0.00154 \cdot 1147} + \frac{1.0255 \text{ ft}^3/\text{sec} \cdot 1852}{\text{ft}^2} + \frac{1.2 \text{ ft}^3/\text{sec} \cdot 1147}{\text{ft}^2} + \frac{0.0255 \cdot 815}{\text{ft}^2} \right]$$

$$= \dot{m} [662.1 + 451.0 + 1063.4 + 398.4 + 20.8]$$

$$= \dot{m} (2595.7) \text{ ft/sec}$$

$$\dot{m} = 4.076 \text{ sl/sec} = \boxed{131 \text{ lbm/sec}}$$

$$(b) \quad A_c = \frac{(1.0255) 131 / 32.17}{0.000578 \cdot 1852} = \boxed{3.90 \text{ ft}^2} \quad \frac{\text{sl ft}^3/\text{sec}}{\text{ft}^2}$$

$$A_f = \frac{(1.2) (131) / 32.17}{0.00154 \cdot 1147} = \boxed{2.77 \text{ ft}^2}$$

11.14

SLTU

$$\left. \begin{aligned} \dot{m}_s &= 3000 \text{ lbm/s} \\ \dot{m}_a &= 375 \text{ lbm/s} \end{aligned} \right\} \text{note } \dot{m}_s / \dot{m}_a = 8.0$$

$$\dot{m}_f = 9.0 \text{ lbm/s}$$

$$u_s = 885 \text{ ft/s}$$

$$u_e = 1255 \text{ ft/s}$$

$$A_f = 6610 \text{ m}^2$$

$$A_e = 1500 \text{ m}^2$$

$$p_f = 14.69$$

$$p_o = 14.69$$

$$p_a = 14.69$$

$$u_e = 0$$

$$F = A_e (p_e - p_a) + A_f (p_e - p_a) \\ + \dot{m}_e (u_e - u_a) + \dot{m}_s (u_s - u_a) + \dot{m}_f u_a$$

$$\dot{m}_e = 375 + 9 = 384 \text{ lbm/s}$$

$$F = 1500(0) + 6610(0)$$

$$+ \frac{384}{32.17} \frac{\text{lbm}}{\text{s}} \frac{\text{ft}}{\text{lbm}} [1255 - 0] + \frac{3000}{32.17} [885 - 0]$$

$$+ 9(0)$$

$$= 0 + 0 + 14980 + 82530 + 0$$

$$\boxed{F = 97510 \text{ lbf}}$$

$$TSFC = \frac{\dot{m}_f}{F} = \frac{9.0 \text{ lbm}}{\text{s}} \frac{3600 \text{ sec}}{\text{hr}} \frac{1}{97510 \text{ lbf}} = \boxed{0.332 \frac{\text{lbm}}{\text{hr lbf}}}$$