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Compressor Effects on Specific Fuel Consumption of Kerosene-fueled Civil Turbofans

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Abstract

All gas turbine propulsion must have a compressor component that develops the pressure rise specified by the cycle. The main objective of the present study is to perform axial compressor pressure ratio effects on the specific fuel consumption of civil turbofans in both ideal and real cycles. At the beginning of this study, ideal and real cycle curves were drawn individually to explain the compressor pressure ratio behavior on the specific fuel consumption in excel and visual programming languages, respectively. At the second step, three dimensional response surfaces of the specific fuel consumption had been drawn according to the compressor pressure ratio. At the end of the study, real engines compressor data were marked on these curves and compared with results obtained in this paper.

Keywords: Turbofan, Compressor, Bypass ratio, Cycle analysis

1. Introduction

Cycle analysis studies the thermodynamic changes of the working fluid (air and products of combustion in most cases) as it flows through the engine. The object of cycle analysis is to obtain estimates of the performance parameters (primarily thrust and specific fuel consumption) in terms of design limitations (such as maximum allowable turbine temperature and attainable component efficiencies), the flight conditions (the ambient pressure, temperature, and Mach number), and design choices (such as compressor pressure ratio, fan pressure ratio, bypass ratio, as soon) (Mattingly, 2002).

The engine design starts with the on-design (or design point) analysis, which presumes that all design choices are still under control, and that the size of the engine has yet to be chosen. The value of parametric cycle analysis depends directly on the realism with the engine components are characterized. For example, the compressor is described by a total pressure ratio and the isentropic efficiency, and if the analysis purpose claims to select the best total pressure ratio for a particular mission, then the choice may determined by the pressure ratio on the variation of efficiency with total pressure ratio must be comprised in the analysis.

In off-design performance analysis no component performances are available so that the component efficiencies as functions of operating conditions must be estimated. Final choice of an engine is based on its off-design performance over the entire aircraft mission. In both forms of analysis, the components of an engine are characterized by the change in properties they produce On-design cycle analysis curves are very important for the cycle analysis of objective engine research. Because it is easy to see effect of the independent design parameters of the engine such as fan pressure ratio and bypass ratio on the dependent parameters such as the specific thrust and specific fuel consumption instead of numerical values (Mattingly, 2002; Oates, 1997).

In this paper, on design analysis of civil turbofan engines with separate flow and non afterburning used in commercial aircraft were analyzed and then effects of compressor pressure ratio on specific fuel consumption for ideal and real cycle analysis for different bypass ratios. Then specific fuel consumption points were evaluated on compressor pressure ratio—bypass ratio—specific fuel consumption response surfaces. New software programs had been developed for this purpose in visual and excel programming language for real and ideal cycles, and MATLAB language for three dimensional cycle curves by Turan (2007).

Ideal and real cycle steady state performance prediction of high bypass turbofan was investigated in Excel (Mert, 2008) and Visual Basic program languages (Turan, 2000) respectively. Compressor pressure ratio effects on specific fuel consumption with different bypass ratios can be easily analyzed in these programs.

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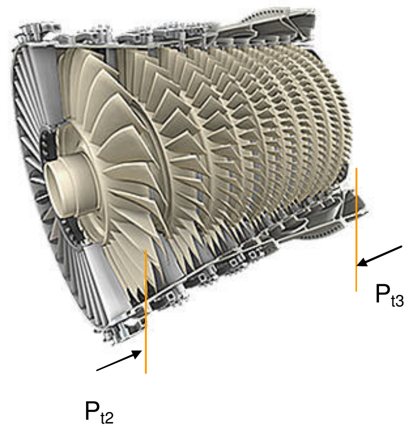
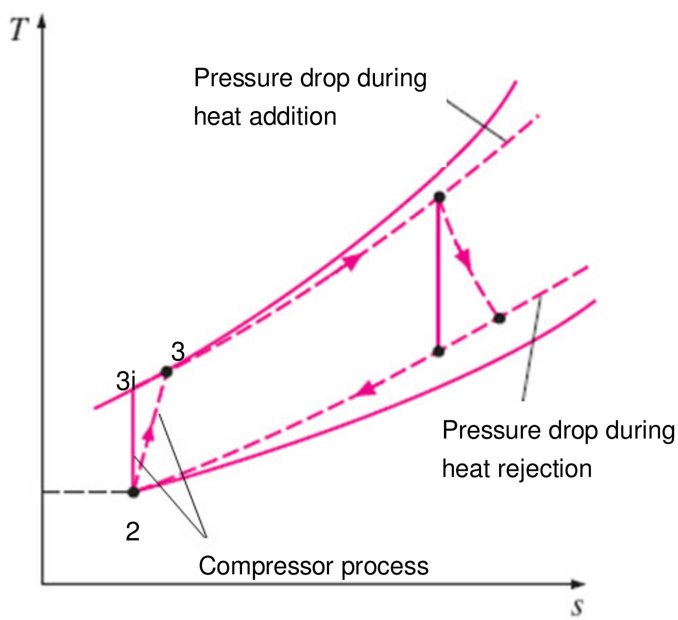
2. Compressor Design Parameters for Parametric Study

Figure 1 shows both the ideal and actual compression processes for a given compressor pressure ratio on a T-s diagram.



(a)



(b)

Figure 1. a) A modern axial flow compressor (Geae, 2008) b) actual (*3*) and ideal (*3i*) compressor processes in T-s diagram (Çengel, 2008)

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Compressors are, to a high degree of approximation, adiabatic. To overall efficiency used to measure a compressor's performance is the isentropic efficiency η_c, defined by

$$\eta_c = \frac{\text{ideal work of compression for given pressure ratio}}{\text{actual work of compression for given pressure ratio}} \tag{1}$$

The actual work per unit mass w_c is h_{t3}- h_{t2} [$=C_p(T_{t3}-T_{t2})$] and the ideal work per unit mass $w_{ci}=h_{t3i}$- h_{t2} [$=C_p(T_{t3i}-T_{t2})$]. Here, h_{t3i} is the isentropic compressor leaving total enthalpy. Compressor isentropic efficiency can be written as follows:

$$\eta_c = \frac{w_{ci}}{w_c} = \frac{h_{t3i} - h_{t2}}{h_{t3} - h_{t2}} \tag{2}$$

For a calorifically perfect gas, it can be written as Equation (3);

$$\eta_c = \frac{w_{ci}}{w_c} = \frac{C_p\left(T_{t3i} - T_{t2}\right)}{T_{t3} - T_{t2}} = \frac{\tau_{ci} - 1}{\tau_c - 1} \tag{3}$$

In Equation (3) τ_{ci} is the ideal compressor temperature ratio which is related to the compressor pressure ratio by the isentropic relationship

$$\tau_{ci} = \pi_{ci}^{(\gamma-1)/\gamma} = \pi_c^{(\gamma-1)/\gamma} \tag{4}$$

Thus we have

$$\eta_c = \frac{\pi_c^{(\gamma-1)/\gamma} - 1}{\tau_c - 1} \tag{5}$$

2. Compressor Pressure Ratio Effects on the Specific Fuel Consumption for Ideal and Real Cycles

The station numbering of a commercial turbofan can be shown engine in Figure 1. Station numbering is most important for thermodynamic study and energy analysis of air breathing engines. Ideal and real cycle equations were given in Appendix 1 and Appendix 2, respectively. Compressor pressure ratio effects on the specific fuel consumption of commercial turbofans for ideal and real cycles can be easily shown in Figure 2 and Figure 3.

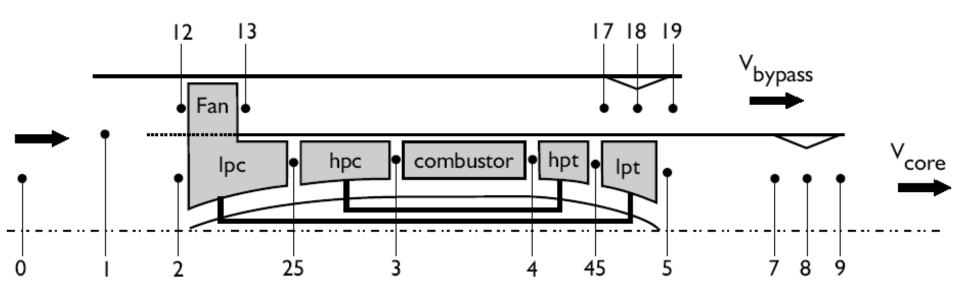

Figure 1. Station numbering of commercial turbofan (Borguet, 2006)

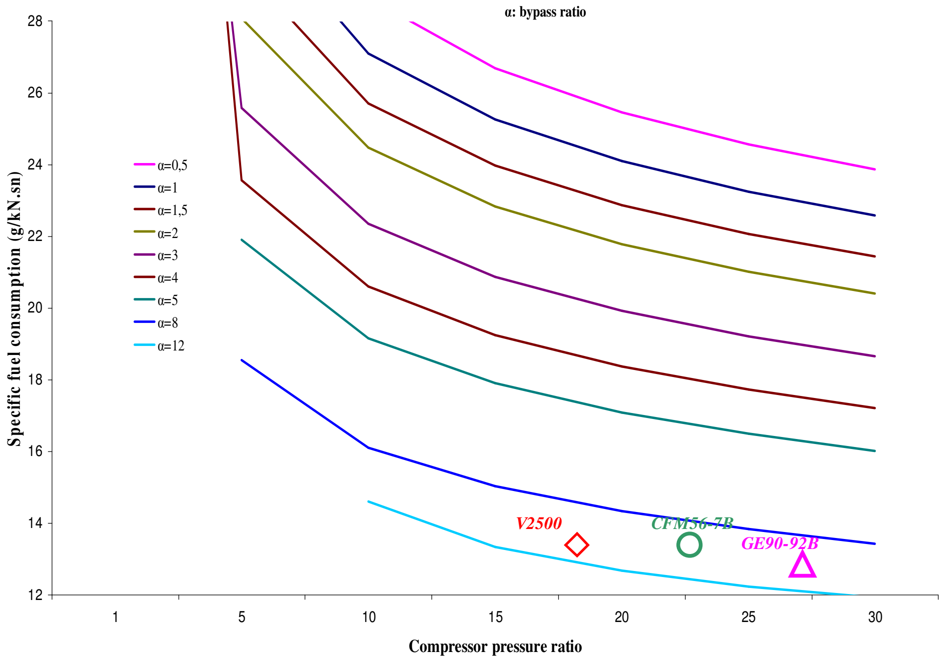

Figure 2. Specific fuel consumption variation with compressor pressure for ideal cycle

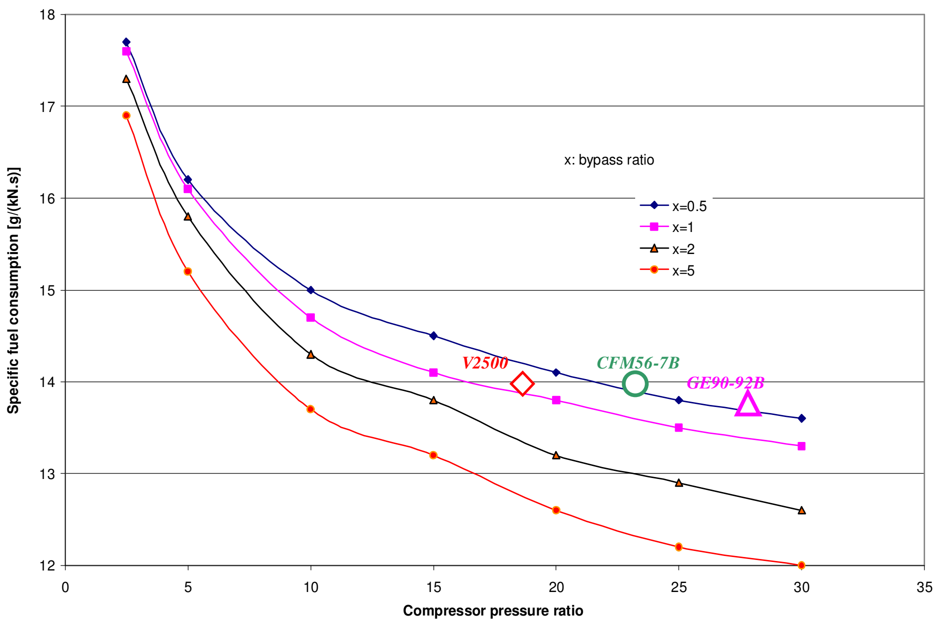

Figure 3. Specific fuel consumption variation with compressor pressure for real cycle

It can be observed in Figure 2 and Figure 3 that while the compressor pressure ratio increases, the specific fuel consumption decreases in ideal and real cycles. V2500, CFM56-7B and GE90-92B engines value are also shown in Figure 2 and Figure 3.

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3. Compressor Pressure Ratio—Bypass Ratio—Specific Fuel Consumption Response Surfaces

Compressor pressure ratio—bypass ratio—specific fuel consumption response surfaces were developed by Turan (2008) in MATLAB programming environment. Parametric calculation can be implemented for observing specific fuel consumption variation according to the compressor pressure ratio and the bypass ratio as a three dimensional and color scaled plots. Specific fuel consumption variation with bypass ratio and compressor pressure ratio can be easily shown in Figure 4 coupled with input parameters in Table 1.

Table 1. On-design parameters for compressor pressure ratio—bypass ratio—specific fuel consumption plots

M_0	T_0 (K)	h_{PR} (kJ/kg)	π_f	T_4(K)	Cpc kJ/(kg.K)	Cpt kJ/(kg.K)	γ_c	γ_t
0.8	220	43100	1.5	1500	1.00488	1.147	1.4	1.33
p_{t4}/p_{t3}	p_{t19}/p_{t13}	e_c	e_f	e_t	η_b	η_m	p_0/p_9	p_0/p_{19}
0.99	0.99	0.90	0.89	0.89	0.99	0.99	0.90	0.90

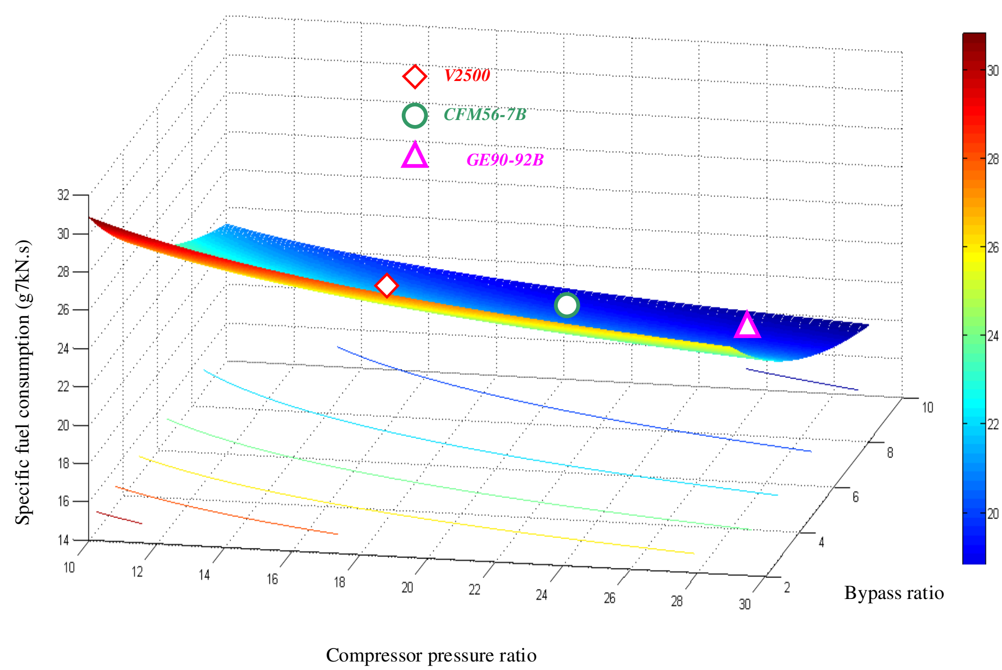
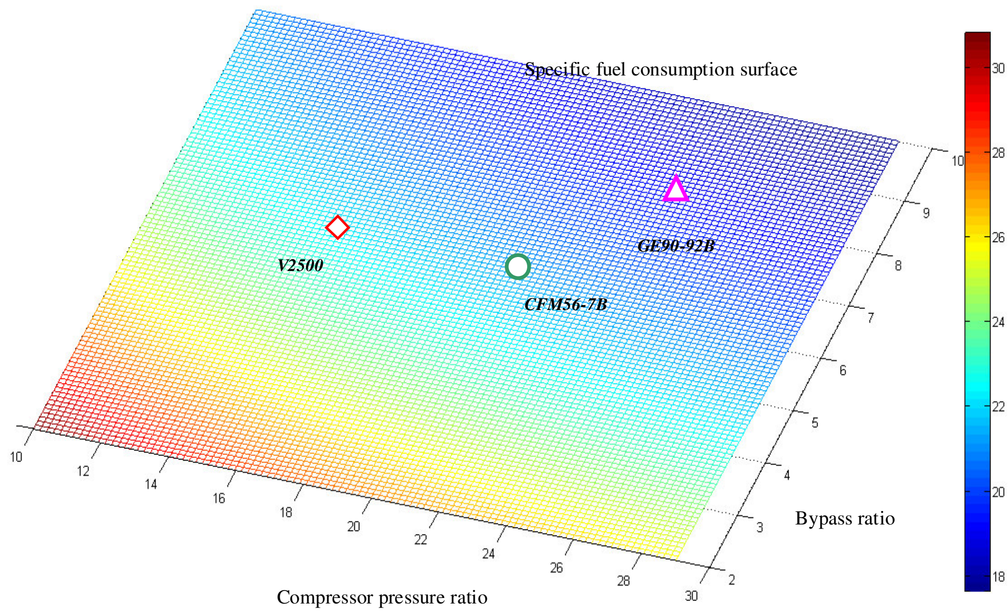


Figure 4. (a)



(b)

Figure 4. Specific fuel consumption color-scaled surface according to bypass ratio and compressor pressure ratio a) sideview b) upper view

4. Conclusions

In this study, firstly new computer software were developed for ideal and real cycle analysis of a turbofan engine and then compressor pressure ratio—bypass ratio—specific fuel consumption response surfaces of high bypass turbofan engine in the conceptual design phase in MATLAB environment. In this regard, three different software programs were developed.

It can be seen that three color scaled surface performance plots of a high bypass turbofan engine are easy to evaluate compressor effects on specific fuel consumption.

Then, additional effects, such as the weight, noise, exergy efficiency and thrust of the commercial engine or its pollutant emissions should be introduced in the model to define new figures of merit.

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Nomenclature

a	Speed of sound, m/s
C_p	Specific heat at constant pressure, kJ/(kg-K)
C_v	Specific heat at constant volume, kJ/(kg-K)
e	Politropic efficiency
f	Fuel –air ratio
F	Thrust, kN
FR	Thrust ratio
$F/\dot{m}_0$	Specific thrust, N.s/kg
g_c	Newton's constant
h_{PR}	Fuel heating value, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
M	Mach number
P	Pressure, Pa
R	Universal gas constant, $m^2/(s^2\text{-}K)$
SFC	Specific fuel consumption, g/(kN.s)
T	Temperature, K
V	Velocity, m/s
α	Bypass ratio
w	specific work

Greek Letters

η	Efficiency
γ	Specific heat ratio
π	Pressure ratio
τ	Temperature ratio
τ_λ	Enthalpy ratio of combustion chamber

Subcripts and supercripts

b	Burner

c Compressor
d Diffuser
e Exit
fn Fan nozzle
i Isentropic
DB Duct bypass
O Overall
P Propulsive
t Total
TH Thermal

Appendix

Appendix 1. Ideal cycle parametric equations for separate flow and no afterburning turbofan

Table E1. Input and output parameters for ideal parametric cycle

Input parameters
$M_0, T_0, \gamma, c_p, h_{PR}, T_{t4}, \pi_c, \pi_f, \alpha$
Output parameters
$F/\dot{m}_0$ f, SFC, η_{TH}, η_P, η_O, FR

Table E2. Ideal parametric cycle equations

Equation	No	Equation	No
$R = \frac{\gamma - 1}{\gamma} C_p$	(e.1)	$\frac{F}{\dot{m}_0} = \frac{a_0}{(1+\alpha) g_c}\left[\frac{V_9}{V_0} - M_0 + \alpha\left(\frac{V_{19}}{a_0} - M_0\right)\right]$	(e.9)
$a_0 = \sqrt{\gamma\ g\ R\ T_0}$	(e.2)	$f = \frac{C_p T_0(\tau_\lambda - \tau_r \tau_c)}{h_{PR}}$	(e.10)
$\tau_r = 1 + \frac{\gamma - 1}{2} M_0^2$	(e.3)	$SFC = \frac{f}{(1+\alpha)(F/\dot{m}_0)}$	(e.11)
$\tau_\lambda = \frac{C_p T_{t4}}{C_p T_0}$	(e.4)	$\eta_{TH} = 1 - \frac{1}{\tau_r \tau_c}$	(e.12)
$\tau_c = \pi_c^{(\gamma - 1)/\gamma}$	(e.5)	$\eta_P = 2M_0 \frac{V_9/a_0 - M_0 + \alpha(V_{19}/a_0 - M_0)}{V_9^2\ /a_0^2\ - M_0^2 + \alpha(V_{19}^2/a_0^2 - M_0^2)}$	(e.13)
$\tau_f = \pi_f^{(\gamma - 1)/\gamma}$	(e.6)	$\eta_0 = \eta_{TH}\eta_P$	(e.14)

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$\frac{V_9}{a_0}=\sqrt{\frac{2}{\gamma -1}\left\{\tau_\lambda-\tau_r\left[\tau_c-1+\alpha(\tau_f-1)\right]-\frac{\tau_\lambda}{\tau_r\tau_c}\right\}}$	(e.7)	$FR=\frac{V_9/a_0-M_0}{V_{19}/a_0-M_0}$	(e.15)
$\frac{V_{19}}{a_0}=\sqrt{\frac{2}{\gamma -1}\left\{\tau_r\tau_f-1\right\}}$	(e.8)		

Appendix 2. Real cycle parametric equations for separate flow and no afterburning turbofan

Table E3. Input and output parameters for real parametric cycle

Input parameters
M_0, T_0, γ_c, C_{pc}, γ_t, c_{pt}, h_{PR}, π_{dmax}, π_b, π_{fn}
π_n, π_{fn}, e_c, e_f, e_t, η_b, η_m, P_0/P_9, P_0/P_{19}, T_{t4}, π_c, π_f, α
Output parameters
$F/\dot{m}_0$ f, SFC, η_{TH}, η_P, η_O

Table E4. Real parametric cycle equations

Equation	No	Equation	No
$R_c=\frac{\gamma_c-1}{\gamma_c}C_{pc}$	(e.16)	$\eta_c=\frac{\pi_c^{(\gamma_c-1)/\gamma_c}-1}{\tau_c-1}$	(e.25)
$R_t=\frac{\gamma_t-1}{\gamma_t}C_{pt}$	(e.17)	$\tau_f=\pi_f^{(\gamma_c-1)/(\gamma_c e_f)}$	(e.26)
$a_0=\sqrt{\gamma_c g_c R_c T_0}$	(e.18)	$\eta_f=\frac{\pi_f^{(\gamma_c-1)/\gamma_c}-1}{\tau_f-1}$	(e.27)
$V_0=a_0M_0$	(e.19)	$f=\frac{\tau_\lambda-\tau_r\tau_c}{h_{PR}\eta_b/(C_{pc}T_0)-\tau_\lambda}$	(e.28)
$\tau_r=1+\frac{\gamma_c-1}{2}M_0^2$	(e.20)	$\tau_t=1-\frac{\tau_r\left[\tau_c-1+\alpha(\tau_f-1)\right]}{\eta_m\tau_\lambda(1+f)}$	(e.29)
$\pi_r=\tau_r^{\gamma_c/(\gamma_c-1)}$	(e.21)	$p_{t9}/p_0=(p_0/p_9)\pi_r\pi_d\pi_c\pi_b\pi_t\pi_n$	(e.30)
$\pi_d=\pi_{dmax}\eta_r$	(e.22)	$M_9=\sqrt{\frac{2}{\gamma_t-1}\left[\left(\frac{p_{t9}}{p_0}\right)^{\frac{(\gamma_t-1)}{\gamma_t}}-1\right]}$	(e.31)

$\tau_\lambda = \frac{C_{pc}T_{t4}}{C_{pc}T_0}$	(e.23)	$\frac{T_9}{T_0} = \frac{\tau_\lambda \tau_t C_{pc}}{(p_{t9}/p_9)^{(\gamma_t-1)/\gamma_t} C_{pt}}$	(e.32)
$\tau_c = \pi_c^{(\gamma_c-1)/(\gamma_c e_c)}$	(e.24)	$\frac{V_9}{V_0} = M_9\sqrt{\frac{\gamma_t R_t T_9}{\gamma_c R_c T_0}}$	(e.33)
$p_{t9}/p_{19} = (p_0/p_{19})\pi_r\pi_d\pi_f\pi_{fn}$	(e.34)	$\frac{F}{\dot{m}_0} = \frac{a_0}{(1+\alpha)g_c}\left[(1+f)\frac{V_9}{V_0} - M_0 + (1+f)\frac{R_t}{R_c}\frac{T_9/T_0}{V_9/V_0}\frac{1-P_0/P_9}{\gamma_c}\right] + \frac{\alpha a_0}{(1+\alpha)g_c}\left[\frac{V_{19}}{V_0} - M_0 + \frac{T_{19}/T_0}{V_{19}/V_0}\frac{1-P_0/P_{19}}{\gamma_c}\right]$	(e.38)
$M_{19} = \sqrt{\frac{2}{\gamma_c-1}\left[\left(\frac{p_{t19}}{p_0}\right)^{\frac{\gamma_c-1}{\gamma_c}} -1\right]}$	(e.35)	$SFC = \frac{f}{(1+\alpha)(F/\dot{m}_0)}$	(e.39)
$\frac{T_{19}}{T_0} = \frac{\tau_\lambda \tau_f}{(p_{t19}/p_{19})^{(\gamma_c-1)/\gamma_c}}$	(e.36)	$FR = \frac{(1+f)\frac{V_9}{V_0} - M_0 + (1+f)\frac{R_t}{R_c}\frac{T_9/T_0}{V_9/V_0}\frac{1-P_0/P_9}{\gamma_c}}{\frac{V_{19}}{V_0} - M_0 + \frac{T_{19}/T_0}{V_{19}/V_0}\frac{1-P_0/P_{19}}{\gamma_c}}$	(e.40)
$\frac{V_{19}}{V_0} = M_{19}\sqrt{\frac{T_{19}}{T_0}}$	(e.37)	$\eta_P = \frac{2M_0\left[(1+f)V_9/a_0 + \alpha V_{19}/a_0 - (1+\alpha)M_0\right]}{\left[(1+f)(V_9/a_0)^2 + \alpha(V_{19}/a_0)^2 - (1+\alpha)M_0^2\right]}$	(e.41)
		$\eta_{TH} = \frac{a_0^2\left[(1+f)(V_9/a_0)^2 + \alpha(V_{19}/a_0)^2 - (1+\alpha)M_0^2\right]}{2h_{PR}(f + f_{AB} + \alpha f_{DB})}$	(e.42)
		$\eta_0 = \eta_{TH}\eta_P$	(e.43)