5

RECOMMENDATIONS

FOR SUPERCHARGED DIESEL ENGINES

PART I : **Engine de-rating on account of ambient conditions**

PART II : **Engine acceptance tests**

CIMAC

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CIMAC-RECOMMENDATIONS for Supercharged Diesel Engines

Part I

Engine De-rating on Account of Ambient Conditions

1. Introduction

The determination of the power of turbocharged internal combustion engines under site conditions which are different from standard conditions is a most complex calculation due to the many parameters involved. The methods of calculation used are left to each manufacturer. The site rating is guaranteed by the manufacturer. The conversion formula given in the following is to confirm to the combustion engine user and manufacturer not conversant with the special calculating methods that the site rating guaranteed will be obtained without excessively overloading the engine and the turbocharger.

The CIMAC formula applies to de-rating from standard reference conditions for an engine with standard turbocharging equipment matched to these standard reference conditions and reduces the engine power rating so as to maintain approximately constant exhaust temperature.

The same formula, however, can be used to de-rate from substitute reference conditions at which the engine would be able to operate at full rated power without exceeding the maximum permissible turbocharger speed or exhaust temperature. These substitute reference conditions may exist for the engine with the standard turbocharging equipment or may be created by re-matching of the turbocharger equipment.

2. Nomenclature

α	=	de-rating factor
a	=	humidity factor
(a	=	0 in case of turbocharged engines where air humidity is not taken into account)
b	=	specific fuel consumption
h	=	altitude above sea level (m)
K	=	de-rating constant
P	=	power output (HP)
P_i	=	indicated power (HP)
p	=	absolute pressure (bar)
p_s	=	saturation vapour pressure (bar)
T	=	absolute temperature (K)
T_c	=	absolute charge air coolant temperature (K)
φ	=	relative air humidity (%)
η_m	=	mechanical engine efficiency at rated output under reference conditions
π	=	boost pressure ratio

Suffixes

- max = maximum
- r = standard reference conditions
- ra = substitute reference conditions
- x = site conditions

3. Standard Reference Conditions

The standard reference conditions are :

Ambient air pressure p_r = 1 bar

Ambient air temperature T_r = 300 K

Entry temperature of the charge air coolant T_{cr} is to be stated by the manufacturer at the standard rating.

For air/air charge coolers

$T_{cr} = T_r$ and $T_{cx} = T_x$

4. De-rating Formula

The general de-rating formula reads as follows :

$$P_x = \alpha \cdot P_r \qquad (1)$$

$$\alpha = K - 0{,}7\,(1 - K).\left(\frac{1}{\eta_m} - 1\right) \qquad (2)$$

$$K = \frac{P_{ix}}{P_{ir}} = \left(\frac{p_x - a\cdot\phi_x\cdot p_s}{p_r - a\cdot\phi_r\cdot p_{sr}}\right)^m .\left(\frac{T_r}{T_x}\right)^n .\left(\frac{T_{cr}}{T_{cx}}\right)^q \qquad (3)$$

The following exponents apply :

	m	n	q
Non-intercooled turbocharged 4-stroke Diesel engines	0,7	2,0	-
Intercooled turbocharged 4-stroke Diesel engines	0,7	1,2	1,0

5. De-rating Procedure

For the calculation of the output under site conditions the following two cases have to be distinguished :

5.1. De-rating from Standard Reference Conditions

If the engine rating at standard reference conditions is limited by factors which would be worsened by reduced ambient pressure, increased ambient temperature or increased coolant temperature at constant power output, the standard values p_r, T_r and T_{cr} should be used in equation (3).

In this case the de-rating constant according to equation (3) becomes for :

5.1.1. 4-stroke turbocharged engines without charge air coolers (Formula CIMAC Q)

$$K_q = \left(\frac{p_x}{p_r}\right)^{0,7} \cdot \left(\frac{T_r}{T_x}\right)^{2,0} \qquad (4)$$

5.1.2. 4-stroke turbocharged engines with charge air coolers (Formula CIMAC S)

$$K_s = \left(\frac{p_x}{p_r}\right)^{0,7} \cdot \left(\frac{T_r}{T_x}\right)^{1,2} \cdot \left(\frac{T_{cr}}{T_{cx}}\right) \qquad (5)$$

5.2. De-rating from Substitute Reference Conditions

If the engine at standard reference conditions is limited by factors which are <u>not</u> worsened by changing ambient conditions as mentioned above, substitute conditions p_{ra} and T_{ra} can be used in equation (3) instead of p_r and T_r. The substitute conditions have to be specified by the manufacturer.

The substitute reference pressure is given by

$$p_{ra} \triangleq p_r \cdot \frac{\pi}{\pi_{max}} \qquad (6)$$

In this case the de-rating constant according to equation (3) becomes for :

5.2.1. 4-stroke turbocharged engines without charge air coolers (Formula CIMAC QA)

$$K_{qa} = \left(\frac{p_x}{p_{ra}}\right)^{0,7} \cdot \left(\frac{T_{ra}}{T_x}\right)^{2,0} \qquad (7)$$

5.2.2. 4-stroke turbocharged engines with charge air coolers (Formula CIMAC SA)

$$K_{sa} = \left(\frac{p_x}{p_{ra}}\right)^{0,7} \cdot \left(\frac{T_{ra}}{T_x}\right)^{1,2} \cdot \left(\frac{T_{cr}}{T_{cx}}\right) \qquad (8)$$

6. <u>Calculation of Specific Fuel Consumption</u>

The fuel consumption under site conditions is calculated from

$$b_x = b_r \cdot K \cdot \frac{P_r}{P_x} \qquad (9)$$

7. <u>Barometric Formula</u>

Where the barometric pressure is not known the ambient pressure above sea level may be determined by the C.I.N.A. (Comission Internationale de Navigation Aerienne) formula

$$p_x = 1,01325\ (1 - 22,57 \cdot 10^{-6}\ h)^{5,255} \qquad (10)$$

Appendix

Example No. 1 : De-rating from standard reference conditions (See chapter 5.1.)

Standard reference altitude	110 m	$p_r = 1$ bar
Site altitude	4000 m	$p_x = 0{,}616$ bar
Mechanical efficiency		$\eta_m = 0{,}85$

$$K_q = \left(\frac{p_x}{p_r}\right)^{0,7} = \left(\frac{0{,}616}{1}\right)^{0,7} = 0{,}712$$

$$\alpha_q = K_q - 0{,}7\ (1-K_q)\cdot\left(\frac{1}{\eta_m} - 1\right)$$

$$= 0{,}712 - 0{,}7\ (1 - 0{,}712)\cdot\left(\frac{1}{0{,}85} - 1\right)$$

$$= 0{,}677$$

The exhaust gas turbocharger is operated at 100 % load of the rated output (point 0, Fig. 1) on its speed limit for continuous operation.

In this case, de-rating for 4000 m of altitude is carried out along line a1, along which turbocharger speed and exhaust temperature remain constant. Site rating in this case is 67,7 % (point P1).

Example No. 2 : De-rating from substitute reference conditions (see chapter 5.2.1.)

Boost pressure ratio under standard reference conditions	$\pi = 2$
Maximum permissible boost pressure ratio	$\pi_{max} = 2{,}36$
Substitute reference pressure	$p_{ra} = 1\cdot\frac{2}{2{,}36} = 0{,}846$ bar
Site altitude 4000 m	$p_x = 0{,}616$ bar
Mechanical efficiency	$\eta_m = 0{,}85$

$$K_{qa} = \left(\frac{p_x}{p_{ra}}\right)^{m} = \left(\frac{0{,}616}{0{,}846}\right)^{0,7} = 0{,}801$$

$$\alpha_{qa} = K_{qa} - 0{,}7\ (1 - K_{qa})\cdot\left(\frac{1}{\eta_m} - 1\right)$$

$$= 0{,}777$$

The turbocharger permits an increase in speed up to an altitude of 1500 m. Up to this altitude, point G2, Fig. 1, the engine is capable of delivering the full 100 % output. From there onward, point G2, the engine is de-rated as per line a2, resulting in a site rating of 77,7 % at 4000 m, point P2.

Example No. 3 : De-rating from substitute reference conditions for increased ambient temperature on site (See chapter 5.2.2.)

Engine with intercooler.

Permissible ambient temperature without de-rating according to the engine manufacturer $T_{ra} = 313\ K$

Ambient site temperature $T_x = 323\ K$

Mechanical efficiency $\eta_m = 0,85$

$$K_{sa} = \left(\frac{T_{ra}}{T_x}\right)^{1,2} = \left(\frac{313}{323}\right)^{1,2} = 0,963$$

$$\alpha_{sa} = K_{sa} - 0,7\ (1 - K_{sa}) \cdot \left(\frac{1}{\eta_m} - 1\right)$$

$$= 0,958$$

Up to 313 K it would be possible to run the engine at the full rating, point G3, Fig. 2. De-rating takes place as per line c3. At 323 K the output is 95,8 %, point P3.

Example No. 4 : De-rating from substitute reference conditions for ambient pressure, ambient temperature and cooling water on site (See chapter 5.2.2.)

Boost pressure ratio under standard reference conditions $\pi = 2,2$

Maximum permissible boost pressure ratio $\pi_{max} = 2,6$

Substitute reference pressure $p_{ra} = 1 \cdot \frac{2,2}{2,6}$

$= 0,846$ bar

Site ambient pressure (3000 m) $p_x = 0,701$ bar

Substitute reference temperature $T_{ra} = 303\ K$

Ambient site temperature $T_x = 308\ K$

Coolant inlet temperature into cooler under reference conditions $T_{cr} = 300\ K$

Coolant inlet temperature into cooler on site $T_{cx} = 313\ K$

Mechanical efficiency $\eta_m = 0,85$

$$K_{sa} = \left(\frac{p_x}{p_{ra}}\right)^{0,7} \cdot \left(\frac{T_{ra}}{T_x}\right)^{1,2} \cdot \left(\frac{T_{cr}}{T_{cx}}\right)$$

$$K_{sa} = \left(\frac{0,701}{0,846}\right)^{0,7} \cdot \left(\frac{303}{308}\right)^{1,2} \cdot \left(\frac{300}{313}\right)^{1,0}$$

$$= 0,825$$

$$\alpha_{sa} = K_{sa} - 0,7\ (1 - K_{sa}) \cdot \left(\frac{1}{\eta_m} - 1\right)$$

$$= 0,825 - 0,7\ (1 - 0,825) . \left(\frac{1}{0,85} - 1\right)$$

$$= 0,803$$

The power output of the engine on site amounts to 80,3 % of the rated power under reference conditinns.

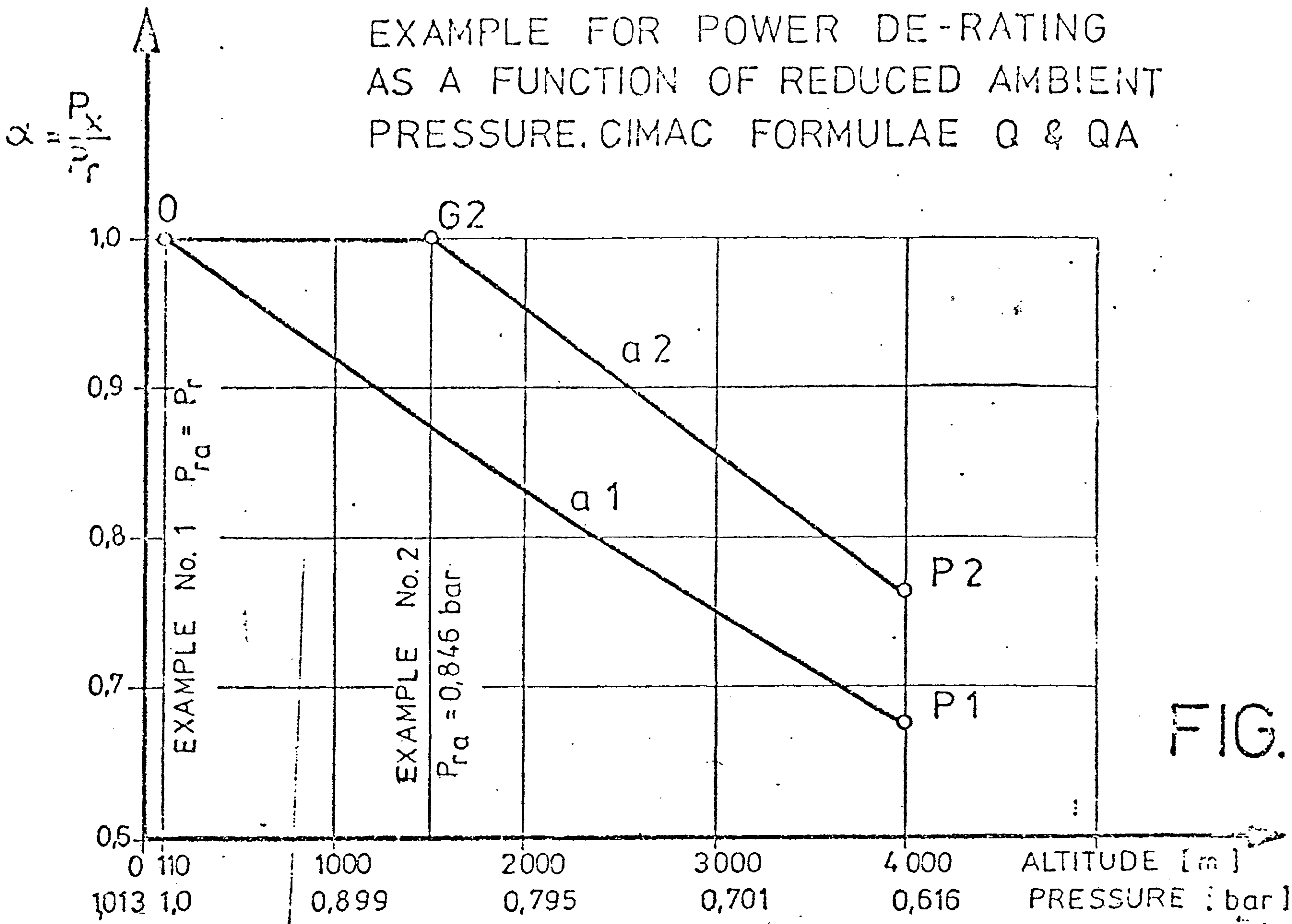

EXAMPLE FOR POWER DE-RATING
AS A FUNCTION OF REDUCED AMBIENT
PRESSURE. CIMAC FORMULAE Q & QA
α = Px/Pr
1,0
0,9
0,8
0,7
0,5
O
G2
a 2
a 1
P2
P1
EXAMPLE No. 1 Pra = Pr
EXAMPLE No. 2 Pra = 0,846 bar
0 110 1000 2000 3000 4000 ALTITUDE [m]
1013 1,0 0,899 0,795 0,701 0,616 PRESSURE [bar]

FIG. 1

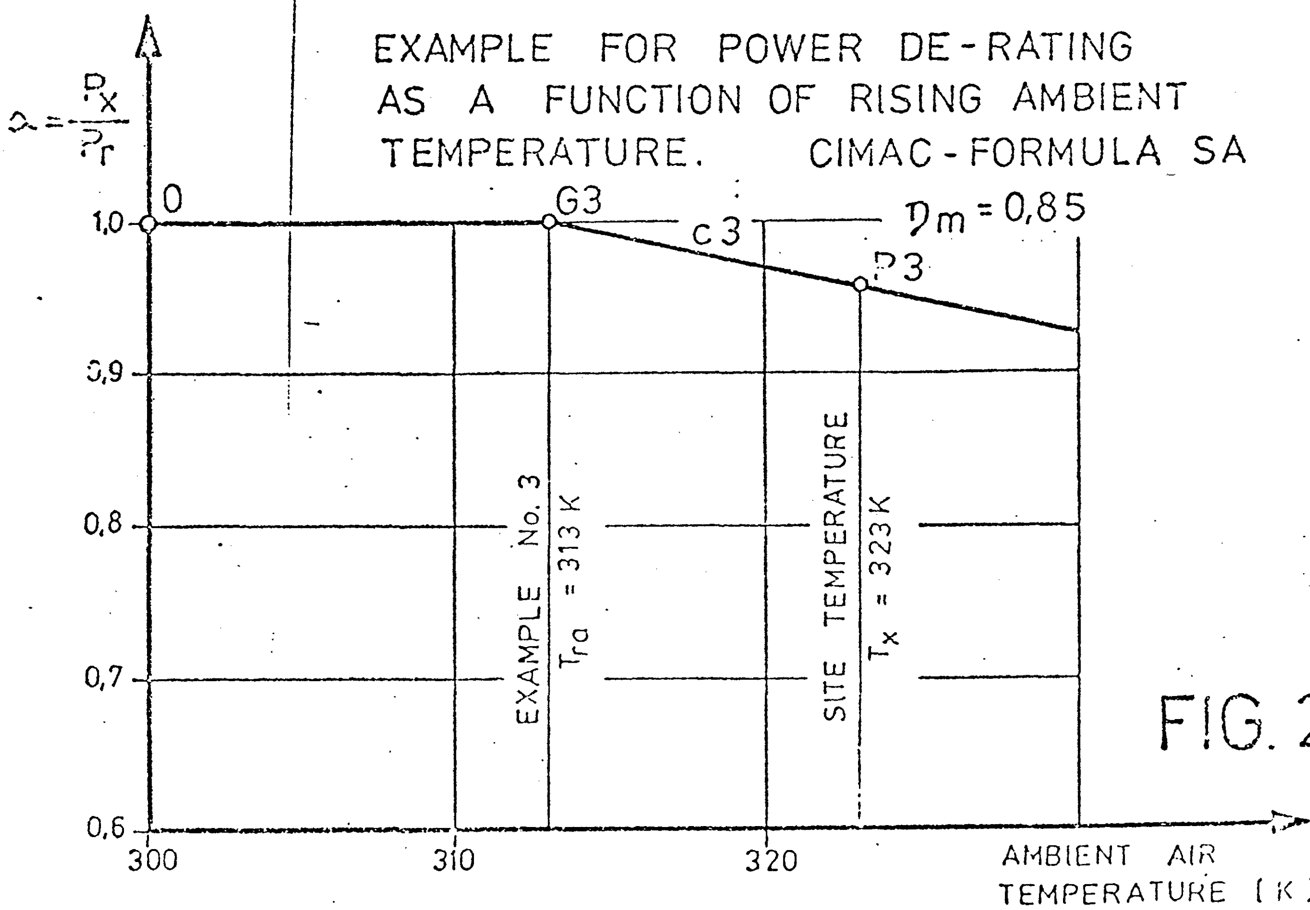

EXAMPLE FOR POWER DE-RATING
AS A FUNCTION OF RISING AMBIENT
TEMPERATURE. CIMAC-FORMULA SA
α = Px/Pr
1,0
0,9
0,8
0,7
0,6
O
G3
c 3
ηm = 0,85
P3
EXAMPLE No. 3 Tra = 313 K
SITE TEMPERATURE Tx = 323 K
300 310 320
AMBIENT AIR TEMPERATURE [K]

FIG. 2

CIMAC-RECOMMENDATIONS
for Supercharged Diesel Engines

Part II

Engine Acceptance Tests

(Appendix E to CIMAC-Recommendations for Diesel Engine Acceptance Tests
or inserted instead of 7.4)

Introduction

The CIMAC-Recommendations for Diesel Engine Acceptance Tests published in January 1967 state on page 15/16

7.4 Engines Pressure-Charged by Exhaust-Gas Turboblower

In the absence of a suitable correction formula, a written agreement is necessary between supplier and client.

Meanwhile further work has been carried out by a CIMAC Committee on turbocharged 4-stroke engines with and without charge air coolers and the clause should now be replaced by the following :

E 7.4 Engines Pressure-Charged by Exhaust-Gas Turboblower

For two-stroke turbocharged engines, in the absence of a suitable correction formula, a written agreement is necessary between supplier and client.

For 4-stroke turbocharged engines, when it is necessary to make a correction for atmospheric conditions, at a given speed, the following correction formula will be used. .

E 7.4.1 Formula CIMAC Q

For 4-stroke engines pressure-charged by exhaust gas turboblower and without charge-air cooler.

$$P_x = \alpha_q \cdot P_r$$

where

$$\alpha_q = K_q - 0{,}7\ (1 - K_q) \cdot \left(\frac{1}{\eta_{mr}} - 1\right)$$

with

$$K_q = \frac{P_{ix}}{P_{ir}} = \left(\frac{T_r}{T_x}\right)^{2,0} \cdot \left(\frac{p_x}{p_r}\right)^{0,7}$$

Note that the correction is independent of the air humidity.

The symbols used have the following meaning

P = nett or brake power

P_i = indicated power

α_q = Power correction factor in the case "CIMAC Q" (turbocharged without charge air cooler)

K_q = ratio of indicated powers in the case "CIMAC Q"

T = absolute temperature

p = barometric pressure

η_{mr} = mechanical efficiency at ~~standard~~ REFERENCE conditions

The suffix "r" corresponds to the values of chosen reference conditions, which may be site conditions or standard reference conditions.

The suffix "x" corresponds to the values of any conditions "x", which may be test conditions.

E 7.4.2 Formula CIMAC S

For 4-stroke engines pressure-charged by exhaust-gas turboblower and with charge-air coolers

$$P_x = \alpha_s \cdot P_r$$

where

$$\alpha_s = K_s - 0{,}7\ (1 - K_s) \cdot \left(\frac{1}{\eta_m} - 1\right)$$

with

$$K_s = \frac{P_{ix}}{P_{ir}} = \left(\frac{T_r}{T_x}\right)^{1,2} \cdot \left(\frac{p_x}{p_r}\right)^{0,7} \cdot \left(\frac{T_{cr}}{T_{cx}}\right)$$

Note that the correction is independent of the air humidity.

α_s = power correction factor in the case "CIMAC S" (turbocharged with charge air cooler)

K_s = ratio of indicated powers in the case "CIMAC S"

T_c = absolute temperature of charge air coolant

Other symbols have the same meaning as in E 7.4.1.

E 7.4.3 Test Procedure

E 7.4.3.1 Engines with or without intercoolers

If an environmental test rig for the simulation of ambient site conditions for engines being adapted to a certain altitude or temperature is not available a substitute power has to be demonstrated under test conditions on the manufacturer's test rig. The substitute power is calculated from the site power with the aid of CIMAC formula "Q", "QA", "S" or "SA". In some cases, correction of the site guaranteed power to test bed conditions may result in abnormal maximum cylinder pressure. In these cases, the power is to be limited to the value at which the maximum cylinder pressure is considered safe by the engine manufacturer for a short test run and the values of interest like fuel consumption, turbocharger speed, exhaust gas temperature, peak pressure, etc., have to be extrapolated for the substitute output.

To assist in the extrapolation of part-load results, it is desirable that the test power should be as high as possible and the manufacturer may alter the test conditions artificially to simulate site conditions more nearly, the following methods being possible :

1. Throttling of the air inlet to the turbocharger coupled with reduction of the exhaust pressure by an extraction compressor to simulate high altitude on site.

2. Increase of charge air coolant temperature within the limits of turbocharger surge to achieve partial compensation for high ambient temperature on site.

3. Increase of air inlet temperature by artificial heating.

E 7.4.3.2 Engines with Intercoolers Adapted to High Ambient Temperature

With supercharged engines having an intercooler the effect of increased ambient temperature can be easily simulated by throttling at the turbocharger inlet. Thus the compressor work can be kept constant as a higher boost pressure ratio compensates a reduced inlet temperature. The throttle ratio for constant compressor work can be taken from graph 1 of the appendix. During the test the boost air temperature after intercooler and the power rating have to be the same as on site.

E 7.4.4 Tolerances of Test Conditions and Power Correction

As a rule the site conditions will not exist on the manufacturer's test bench. A power correction is not applied unless the test ambient pressure differs more than ± 0,02 bar or ambient temperature more than ± 6 K or coolant temperature at inlet more than ± 6 K from reference site conditions. If the deviations are larger than mentioned above the power rating on the test bench has to be corrected by the aid of CIMAC formula "Q" or "S" from the reference site conditions to the test-bed conditions which are subject to the same tolerances as given above.

E 7.4.5 Fuel Consumption Correction Formula for Atmospheric Conditions

The formula of 7.3 will also be used for engines pressure-charged by exhaust-gas turboblower.
It reads

$$b_x = \beta \cdot b_r$$

where

$$\beta = \frac{K}{\alpha} = \frac{K}{K + 0{,}7\,(1 - K)\cdot\left(\frac{1}{\eta_{mr}} - 1\right)}$$

In this formula :

b = specific fuel consumption

β = consumption correction factor (see also § E 7.4.1 and § E 7.4.2 for the meaning of other symbols)

E 7.4.6 Examples

a.- A 4-stroke turbocharged engine with a charge air cooler is to develop 850 h.p. with an adapted turbocharger under site conditions of :

p_r = 0,7 bar T_{cr} = 300 K

T_r = 330 K η_{mr} = 0,85

What power should be developed under test conditions of :

$p_x = 1{,}0$ bar

$T_x = 300$ K

$T_{cx} = 280$ K

$$K_s = \left(\frac{330}{300}\right)^{1,2} \cdot \left(\frac{1,0}{0,7}\right)^{0,7} \cdot \left(\frac{300}{280}\right)$$

$$= 1{,}12 \cdot 1{,}28 \cdot 1{,}07 = 1{,}53$$

$$\alpha_s = 1{,}53 + (0{,}7 \cdot 0{,}53 \cdot 0{,}18) = 1{,}60$$

Thus the engine should be tested at

$1{,}60 \cdot 860 = 1375$ h.p.

But suppose there is a limitation in maximum cylinder pressure which the manufacturer imposes at a power of 1100 h.p. then the engine is tested at part loads up to 1100 h.p. and the results are extrapolated to 1375 h.p.

b.- Suppose the manufacturer of the engine mentioned under a. arranges to throttle the air intake and adjusts the charge air coolant temperature in order to simulate the temperature influence on the engine.

For a temperature ratio

$\frac{T_r}{T_x} = \frac{330}{300} = 1{,}10$ one can take from graph 1

a throttle ratio $\frac{p_1}{p_x} = 0{,}925$

at turbocarger inlet for an assumed

boost pressure ratio of $\frac{p_2}{p_x} = 2{,}5$

To compensate the temperature influence the boost air temperature has to be set to the value anticipated under site conditions by adjusting either water flow or the coolant temperature or both together.

Thus the power correction factor for the influence of ambient pressure becomes

$$K_s = \left(\frac{1,0}{0,7}\right)^{0,7} = 1{,}28$$

$$\alpha_s = 1{,}28 + (0{,}7 \cdot 0{,}28 \cdot 0{,}176) = 1{,}31$$

Note that the ambient pressure before throttle has to be inserted in the equation to assess the influence of pressure.

In this case the engine has to be demonstrated at

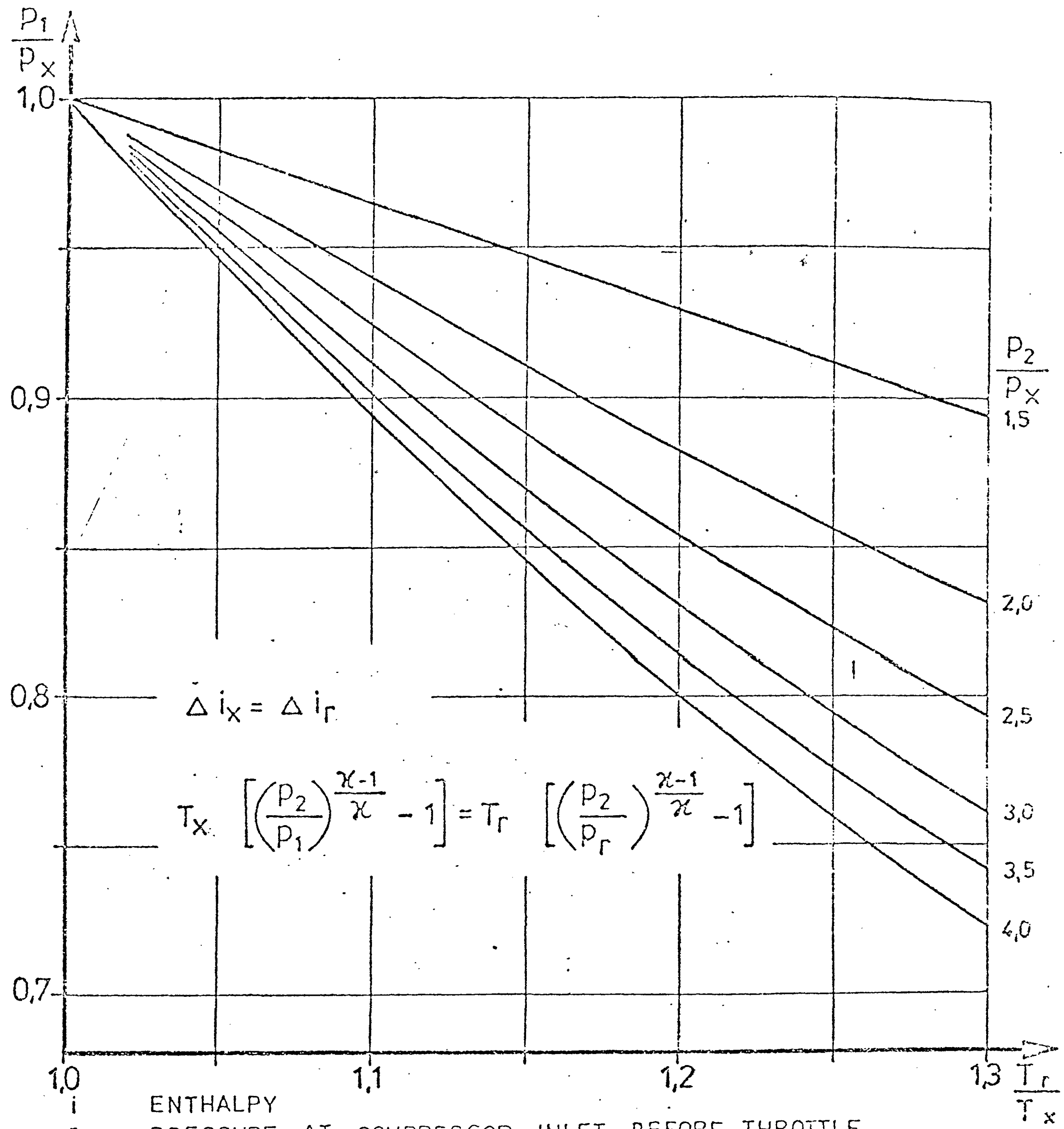
$1,31 \cdot 860 = 1127$ h.p.

c.- If the measured fuel consumption at this load of example b. on test is 175 g/hp.hr.

then with $\beta = \frac{K}{\alpha} = \frac{1,28}{1,31}$

the fuel consumption corrected to site conditions is

$$b_r = \frac{b_x}{\beta} = 175 \cdot \frac{1,31}{1,28} = 179 \text{ g/hp.hr.}$$



i	ENTHALPY
p_x	PRESSURE AT COMPRESSOR INLET BEFORE THROTTLE
p_1	PRESSURE AT COMPRESSOR INLET AFTER THROTTLE
p_2	PRESSURE AT COMPRESSOR OUTLET
T_x	AMBIENT TEST TEMPERATURE
T_r	AMBIENT SITE TEMPERATURE
$\varkappa$	RATIO OF SPEC. HEAT

SIMULATION OF HIGH AMBIENT SITE TEMPERATURE BY THROTTLING OF TURBOCHARGER INLET

ASSUMPTIONS:

EQUAL ISENTROPIC COMPRESSOR WORK
EQUAL PRESSURE AT COMPRESSOR OUTLET
EQUAL TEMPERATURE AFTER INTERCOOLER
EQUAL MASS FLOW

FIG. 1