THE IMPACT OF ATMOSPHERIC CONDITIONS ON GAS TURBINE PERFORMANCE

تأثير الظروف المناخية على معامل أداء التوربينات الغازية

By

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الخلاصة — هذا البحث يهتم بدراسة تأثير الطقس الحار على معامل الأداء للتوربينات الغازية والتي تعمل في المناطق ذات المناخ الحار مثل الكويت وباقي الدول الخليجية ، ومن المعلوم أن درجة الحرارة تصل في بعض الأحيان الى ٦٠ مْ . وكذلك الرطوبة النسبية التي تصل هي الأخرى الى ١٠٠ ٪ في بعض الأحيان مما يكون له بلا شك تأثير على أداء هذه التوربينات . كذلك اهتم البحث بدراسة تأثير تغيير الضغط الجوي ومن المعلوم أن بعض المحركات الغازية مثلما التي تعمل بالطائرات تصل ارتفاعها الى ٢٠٠٠ متر أعلى من مستوى سطح البحر . كذلك كانت هذه الدراسة متناولة لتأثير كل من درجة الحرارة والرطوبة النسبية والضغط الجوي على معامل أداء المحركات الغازية . وقد أجريت هذه الدراسة أخذا في الاعتبار أربع حالات لدرجات الحرارة القصوى عند مدخل التوربين الغازي وهي ١٠٠٠ ، ١٢٠٠ ، ١٤٠٠ ، ١٦٠٠ درجة حرارة مطلقة . كما أجريت هذه الدراسة أيضا عند الأحمال الكاملة والجزئية للتوربين الغازي. كما تمت المقارنة بين هذه الدراسة والنتائج المتحصل عليها مع المواصفات المقدمة من بعض الشركات الصناعية لهذه الأنواع من المحركات التوربينية . وأظهرت مدى حيود معامل أداء التوربينات الغازية بسبب تلك الظروف الجوية المعنية عن المواصفات التي تقدمها تلك الصانعة

ABSTRACT

In a hot summer climate, as in Kuwait and other Arabian Gulf countries, the performance of a gas turbine deteriorates drastically during the high temperature hours (reaches up to 60 °C in Kuwait). This occurs when the power demand is the largest. This necessitates the increase of the gas turbine installed capacities to balance this deterioration. Gas turbines users are becoming aware of this problem as they depend more on gas turbines to satisfy their needs of power and process heat for desalination due to the recent technical and economical development of the gas turbines.

This paper is devoted to study the impact of atmospheric conditions, such as ambient temperature, pressure, and relative humidity on gas turbine performance. The reason for considering the air pressures different than standard atmospheric pressure of the compressor inlet is the variation of this pressure with the altitude. This can generalize the results of this study to include the cases flights at high altitudes. A fully interactive computer programme based on the derived governing equations is developed. The effects of typical variations of atmospheric conditions on the power output and efficiency are considered. These include ambient temperature (range from 20 to 60 °C), altitude (range from zero to 2000 m above sea level) and relative humidity (range from zero to 100%). The thermal efficiency and specific net work of a gas turbine were calculated at different values of maximum turbine inlet temperature (TIT) and variable environmental conditions. The value of TIT is a design factor which depends on the material specifications and the fuel air

ratio. Typical operating values of (TIT) in modern gas turbines were chosen for this study 1000, 1200, 1400 and 1600 K. Partial loads were also considered in the analysis as well as full load.

Finally the calculated results were compared with the actual gas turbine data supplied by manufacturers.

NOMENCLATURE

CP	Specific heat of working substances at constant pressure (Kj/Kg K)
$\underline{f}$	Theoretical fuel air ratio (Kg. fuel/Kg. air)
$\bar{f}$	Actual fuel air ratio (Kg. fuel/Kg. air)
H	Humidity air ratio (Kg. moisture/Kg. air)
h	Enthalpy (Kj/Kg.)
LHV	Lower heating value (enthalpy of reactions) (Kj/Kg.)
M	Molecular weight
NMW	Mixture molecular weight
$\underline{R}$	Gas constant (Kj/Kg. K)
$\bar{R}$	Universal gas constant (Kj/Kg. mol. K)
RH	Relative humidity of air (%)
P	Pressure (N/m^2)
PR	Pressure ratio (compression or expansion)
T	Temperature (K)
TIT	Maximum turbine inlet gas temperature (K)
W	Specific net work (net work per unit mass of air (Kj/Kg. of air)
η	Overall thermal efficiency (%)
γ	Specific weight of substances (N/M^3)
ρ	Density (Kg/m^3)
ϕ	Relative humidity (%)

Subscripts:

a	Ambient air	c	Compressor
d	dry air	f	Fuel
m	mixture	P	Products
s	moisture	ss	saturated vapor
t	turbine	V	Vapor

1, 2, 3 and 4 cycle state points, Fig. 1 (b)

INTRODUCTION :

In the last three decades, gas turbine have played a unique role in the power industry. Because of their relatively low initial cost, gas turbines are frequently used for emergency services and handling daily peak loads on a power plants system. In many systems gas turbines are also operated in the spinning reserve mode.

Recent improvements in the gas turbine performance led to the increase of the gas turbines efficiency. Many researchers have worked on the evaluation of gas turbine performance. Recently, Yousef et al (1987) have re-evaluated the thermophysical properties of the combustion gases of the gas turbine engines using the Soave-Redlich-Kwong (SRK) equation of State. The properties which have been considered in their work were density, specific heat at constant pressure enthalpy, entropy, viscosity, and thermal conductivity. The Soave-Redlich-Kwong (SRK) equation of state generally predicted better values for thermophysical properties than those predicted by the virtual equation of state. Also the thermodynamics of compression and expansion process in turbomachinery are reanalysed by (Sergio et al 1986).

The present study is carried out on the impact of atmospheric conditions on a gas turbine performance. It is well known that the gas turbine performance is affected by varying atmospheric conditions; such as the temperature, pressure and relative humidity. A computer programme is especially designed to calculate overall thermal efficiency and the specific net work from the simple cycle gas turbine. These calculations were carried out for various combustor discharge temperature (TIT) and pressure ratio also. Partial loads are considered as well as full load during these calculations.

THEORETICAL ANALYSIS :

Due to the simplicity in design of the simple cycle gas turbine, it is the most used topping cycle in todays combined plants. The arrangement is illustrated schematically in Fig. 1 (a) shows the flow diagram for the cycle under consideration, and its thermodynamic state points are illustrated on temperature-entropy cordinates in Fig. 1 (b). The fuel is assumed to be methane. All gaseous mixtures considered in the calculations may be treated as mixtures of varying proportions of three components. These components are: air (77.44 per cent N_2, 20.76 per cent O_2 0.92 per cent A_r, 0.85 per cent H_2O, 0.03 per cent CO_2); water (100 per cent H_2O) and stoichiometric gases (75.16 per cent N_2, 19.58 per cent H_2O, 9.43 per cent CO_2, 0.83 per cent Ar). Polynominal fits for the specific heats of each of these three components as a function of temperature are used in the calculators. The specific enthalpy is treated as the sum of chemical components and thermomechanical components.

The operating principle of gas turbine is simplified as the following. Basically ambient air is drawn into a multistage compressor when it is compressed to about 10 times atmospheric pressure. The compressed air then passes through the combustion chamber where fuel is injected and burned. The products of combustion enter the turbine and expand to approximately atmospheric pressure. Part of the work developed by the turbine is used to drive the compressor while the remainder is delivered to equipment external to the gas turbine.

Therefore, the gas turbine performance varies significantly with compressor inlet air conditions, mainly the atmospheric temperature, pressure and relative humidity. Gas turbine design ratings are usually based upon standard conditions. The standard conditions differ from country to country. One of the popular standard is that of the International Standards Organization (ISO). The site conditions at this standard case are: sea level altitude (101.325 KPa, 15°C and 60 per cent relative humidity).

In the present study the effect of atmospheric conditions on the gas turbine, performance was taken into consideration. A computer programme is designed especially for calculating the overall thermal efficiency and specific output work. The governing equations are;

a) Compression Process: For a given polytropic efficiency, the pressure ratio, temperature and thus other state variables for each stream can be calculated. The specific enthalpy can be calculated from the specific heat polynomials.

$$h = \int_{T_1}^{T_2} CP_a(T)\,dt \qquad \ldots (1)$$

where ;

$$Cp_a = CP_d + H * CP_s \qquad \ldots (2)$$

$$CP_d = [28.11 + 0.001967T + 0.4802 \times 10^{-5} T^2 - 1.966 \times 10^{-9} T^3]/28.97 \qquad \ldots (3)$$

where, 28.97 is the molecular weight of dry air

$$CP_s = [32.24 + 0.001923T + 1.055 \times 10^{-5}T^2 - 4.187 \times 10^{-9}T^3]/ 18.015 \qquad \ldots (4)$$

where, 18.015 is the molecular weight of vapor

$$\text{Humidity ratio, } H = 0.622 \frac{p_v}{p_d} = 0.622 \frac{p_{ss} \cdot \Phi}{p_a - p_v} \qquad \ldots (5)$$

$$\text{Steam mass fraction (SMF)} = \frac{H}{1 + H} \qquad \ldots (6)$$

$$\text{Air mass fraction (AMF)} = 1 - \text{SMF} \qquad \ldots (7)$$

$$\text{The molecular weight of mixture (MMW)} = \frac{1}{\frac{SMF}{18.015} + \frac{AMF}{28.97}} \qquad \ldots (8)$$

$$\text{Gas constant of mixture } (R_{mixture}) = \frac{\bar{R}}{MMW} = \frac{8.3143}{MMW} \qquad \ldots (9)$$

$$\text{Mean specific heat at constant pressure } (C_{p_m}) = \frac{C p_1 + C p_2}{2} \qquad \ldots (10)$$

$$\text{Mean specific heat at constant volume } (Cv_m) = Cp_m - R_{mixture} \qquad \ldots (11)$$

$$\text{Isentropic exponent (K)} = \left(\frac{C p}{C v} \right)_m \qquad \ldots (12)$$

$$T_{2s} = T_1 (PR)^{\frac{k-1}{k}} \qquad \ldots (13)$$

By assuming constant isentropic efficiency η_{is} for the compression process, then

$$T_2 = \frac{T_{2s}}{\eta_{is}} + T1 \left(1 - \frac{1}{\eta_{is}} \right) \qquad \ldots (14)$$

where, η_{is} can be considered equal to 0.87 (see Yousef et al 1987)

Then the required work per unit mass for the compressor is equal to :

$$W_c = cp_m \left[\frac{T_{2s}}{\eta_{is}} + T1 \left(1 - \frac{1}{\eta_{is}} \right) - T1 \right] \qquad \ldots (15)$$

b) Combustion Process :

The specific heat of mixture at the combustion chamber entrance is defined as :

b.1 Before Combustion :

$$C_{pm} = C_{pa2} + (f/a)\, C_{pf} \qquad \ldots (16)$$

where ;

f/a is the fuel air ratio, C_{pa2} is the specific heat of moist air at compressor outlet, and

C_{pf} is the specific heat of fuel at combustion chamber inlet.

b.2 After Combustion :

The specific heat of gaseous products after combustion may be determined by using a mathematical model formulated using regression analysis to relate combustion temperature and fuel to air ratio to the specific heat of products gaseous. The values of C_p for different fuel air rations given in (Keenan and Kage 1984) were calculated in the form of the followin equations;

$$C_{p_p} = 1.01 + 0.32 \left(\frac{T3 - 400}{1400} \right) - 0.04 \left(\frac{T3 - 400}{1400} \right)^2 (\text{for } f/a = 0) \qquad \ldots (17)$$

$$C_{p_p} = 1.03 + 0.32 \left(\frac{T3 - 400}{1400} \right) - 0.02 \left(\frac{T3 - 400}{1400} \right)^2 (\text{for } f/a = 0.0135) \qquad \ldots (18)$$

$$C_{p_p} = 1.05 + 0.34 \left(\frac{T3 - 400}{1400} \right) - 0.02 \left(\frac{T3 - 400}{1400} \right)^2 (\text{for } f/a = 0.077) \qquad \ldots (19)$$

Any value in between these range limits can be interpolated to get the exact value of C_{p_p} gas.

Hence, the value of $C_{p\ \text{mixture}}$, after combustion, can be determined by using the following relation:

$$C_{pm3} = C_{pp3} + H\ C_{ps3} \qquad \ldots (20)$$

Then, the heat transfer per unit mass into the combustion chamber can be calculated this way;

$$Qin = \int_{T2}^{T3} [\, C_{pm3}\,(T) * T_3 - C_{pm2}\,(T) * T_2 \,]\ d\,T \qquad \ldots (21)$$

C- Gas Turbine :

The actual gas turbine work is given by ;

$$W_{T.ac} = \frac{W_{T.The}}{0.95 + (f/a)} \qquad \ldots (22)$$

where $W_{T.ac}$ is the actual work per unit mass of the combustor product, $W_{T.The}$ is the theoritical work per unit mass of air inlet to the compressor, 0.95 is the ratio of the air after combustion assuming 5% air loss compressor and f/a is the fuel to air ratio.

$$\frac{T_3}{T_{4s}} = \left(\frac{P_3}{P_4} \right)^{\frac{k-1}{k}} \qquad \ldots (23)$$

where ;

$(p_3/p_1) = PR * 0.97$

(0.97 is considered to account for the duct pressure loss)

$P_4 = 101.325/0.99$

(0.99 is considered to account for the exit pressure loss).

T_{4s} is the isentropic temperature at turbine exit

$$C_{pm.g} = (C_{p_{p3}} + C_{p_{p4}}) / 2 \qquad \ldots (24)$$

$$C_{V\ m.g} = C_{p\ m.g} - R_p \qquad \ldots (25)$$

$$K_{m.g} = (C_{p\ m.g} / C_{v\ m.g})_p \qquad \ldots (26)$$

Therefore ;

$$T_{4s} = T_3 / (P_3 / P_4)^{\frac{k-1}{k}} \qquad \ldots (27)$$

Hence, the turbine output work is given by

$$WT.ac = C_{p\ m.g} * 0.95 + (\hat{l}/a) * (T3 - T4s) * \eta_T \qquad \ldots (28)$$

$$\text{Then ;}\ \eta_{th} = (W_{T.ac} - Wc)/Qin \qquad \ldots (29)$$

Finally the computer programme is written in FORTRAN language and run at Kuwait University Computing Centre.

Equations 1 to 29 results were repeated to get the converged results. Each computer run in stored until the new result comes out. A checking between the new and old results are printed out. Otherwise the iteration process takes place.

RESULTS AND DISCUSSIONS:

The effect of atmospheric conditions (temperature, pressure, and rlative humidity) on the gas turbine performance is studied. For this purpose a full computer programm is constructed using the formulas which were derived from the previous section. The effect of atmospheric pressure is studied on the basis of change of altitude from zero to 2000 m above sea level. Also the range of study for the ambient temperature and relative humidity are considered from-20 to 60°C, and zero to 100 per cent respectively. Net specific work and overall thermal efficiency are calculated for various values of maximum turbine inlet temperature (TIT), and pressure ratio. The values of maximum turbine inlet temperature are taken as 1000, 1200, 1400 and 1600 K, while the values of pressure ratio considered in the calculation are 2, 4, 6, 8, 10, 12, 14 and 16.

Figure 1. shows the simple cycle gas turbine arrangement considered in this study. Natural gas is assumed to be the fuel being used in this analysis. However, the properties of any type of fuel can be fed to the computer program to get the exact results. Also the efficiencies of the compressor, the gas turbine and the combustion chamber are assumed equal to 87%, 89% and 97% respectively. The values of the duct pressure loss, and exit pressure gain are also assumed 97% and 99% respectively. These assumptions have been taken from manufacturer's catalogues to approach the real results.

Figure 2. shows the net work at various ambient temperatures and different maximum inlet temperatures (TIT). The increase of the maximum inlet temperature (TIT) increases

the net work. These net work values decrease as the atmospheric air temperature increases for the same TIT. The effect of the atmospheric air temperature on the thermal efficiency is also indicated through Figs. 7, 8, 9 and 10. Similarly , the effect of atmospheric air temperature on the thermal efficiency is seen to follow the same trend of the net work.

The effect of pressure ratio on both net work and thermal efficiency are clearly shown in Figs. 3, 4, 5, 6 and Figs. 7, 8, 9, 10 respectively.

Figure 3 shows the change of net work with various values of pressure ratio at constant maximum turbine Inlet temp. value of 1000 k, and various atmospheric temp. In this Fig. the increase of pressure ratio value to 5, increase the net work for all considered atmospheric temperatures. Beyond pressure ratio equal to 5, the increase of the pressure ratio decreases the net work output. However, the decreasing rate is lowered by decreasing the atmospheric temperatures.

Figure 4 indicates how the net works varies with the pressure ratio when the maximum turbine inlet temperature is considered constant value of 1200 k, while the atmospheric temperature values are varied. The net work is increased with the increase of pressure ratio when the latter is less than 8. The increase of pressure ratio beyond 8, decreases the net work for atmospheric temperatures of 310, 320, and 330. However, the increase of pressure ratio beyond 8 does not affect of the net work for atmospheric temperature of 270, and 280 K.

The same effects on the net work were observed, as shown in Fig. 5 with the change of pressure ratio for constant maximum turbine inlet temperature of 1400 K, and variable atmospheric temperatures. But Fig. 6 shows that the increase of pressure ratio increases of the net work values at all considered atmospheric temperatures, and at constant maximum turbine inlet temperature of 1600 K.

Figures 9 and 10 show the thermal efficiency at various pressure ratios and atmospheric temperatures and constant maximum turbine inlet temperatures of 1400, and 1600 k respectively. The increase of pressure ratio increases the thermal efficiency in all the considered cases. For a pressure ratio range less than 9, the increase of this pressure ratio causes the increase of the thermal efficiency for constant maximum inlet temperature of 1000 k as shown in Fig. 7. Beyond pressure ratio equal to 9, the increase of this pressure ratio decreases the thermal efficiency again at all considered values of the assumed atmospheric temperature. However, at higher values of atmospheric temperature, the rate of the thermal energy increase with the pressure ratio is getting smaller.

Figure 8, shows the same trend of thermal efficiency with the pressure ratio for maximum turbine inlet temp. of 1200 k. In Fig. 8 the increase of pressure ratio, in the range beyond 10, has little affect the thermal efficiency values when the atmospheric temperature values are equal to 250 and 270 K, but the values of thermal efficiency decrease as the pressure ratio increases when the atmospheric values are in the range of 290-330 K. The atmospheric pressure has no real effect on the efficiency and work output per unit mass. However, the atmospheric pressure has a noticeable effect on the specific power output per unit volume. The important of this point comes from the facts that the compressor succed almost a constant volume. An increase of the specific volume (due to lowering atmospheric pressure) decreases the mass of air intake and consequently the power output. This means that by decreasing the compressor inlet pressure (at changing the altitude above sea level) improves the gas turbine arrangement thermal efficiency.

The effect of the relative humidity on the gas turbine arrangement thermal efficiency and net work are presentd in Figs. 11, and 12 respectively. In both figures no effect is noticed for atmospheric temperatures of 250, 270 and 290 K, while at higher atmospheric air temp. (greater than 310 K), the increase of relative humidity decreases in the net work values and increases in the thermal efficiency values.

Effect of atmospheric temperature on the gas turbine arrangement thermal efficiency and the net work values, when the partial loads are considered, are shown in Figs. 14, and 15 respectively. The increase of atmospheric air temperature decreases both thermal efficiency and net work at all partialload values.

Figure 13, also shows the comparison results between the new predictions along with Brown Boveri Company (BBC) manufacture. Both results are shown clearly in good agreement.

CONCLUSION :

The performance of gas turbine is greatly affected by the atmospheric weather conditions, such as ambient temperature, pressure, and relative humidity. Among the three, ambient temperature has the greatest effect on gas turbine efficiency, and net work. This effect seems to increase with increasing turbine inlet temperature and pressure ratio. The ambient pressure effects the work output per unit volume only, and has no effect on either the net work per unit mass nor thermal efficiency. Also the relative humidity has a negligible effect on both thermal efficiency and net work per unit mass, at low atmospheric temperature. However, decrease the efficiency and increases in net work at higher values of atmospheric air temperature and turbine inlet temperature.

Finally the effect of atmospheric air temperature, and relative humidity on the net work output per unit mass and thermal efficiency of a gas turbine arrangement are computed and studied.

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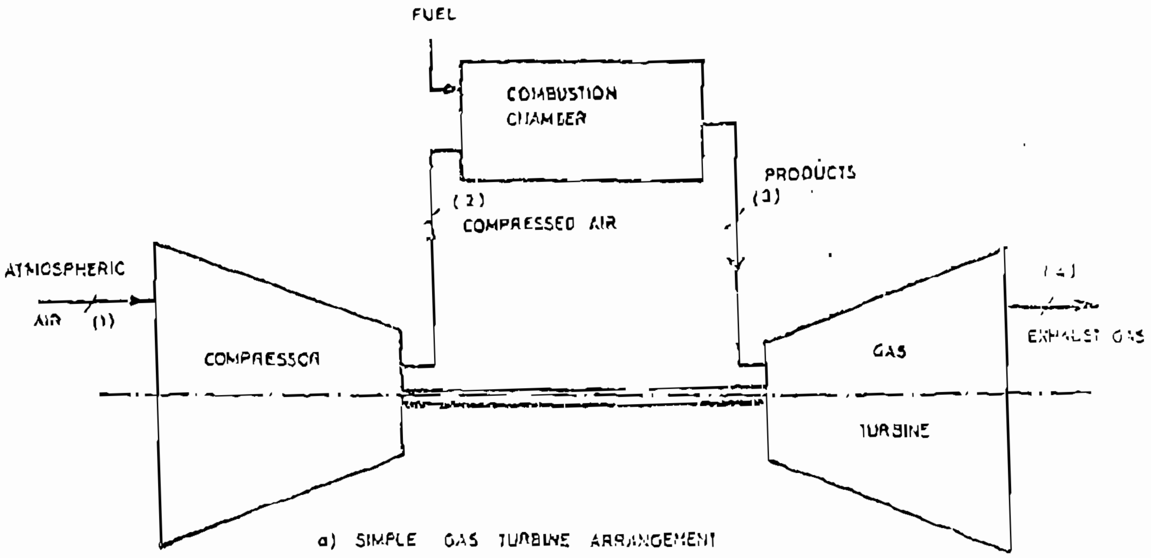
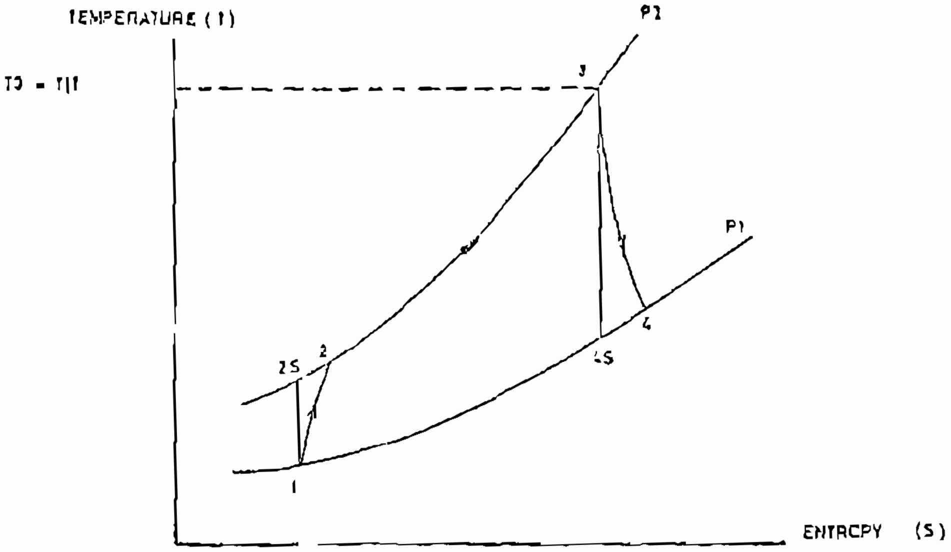


a) SIMPLE GAS TURBINE ARRANGEMENT



b) T-S DIAGRAM

Figure 1. Basic gas turbine engine

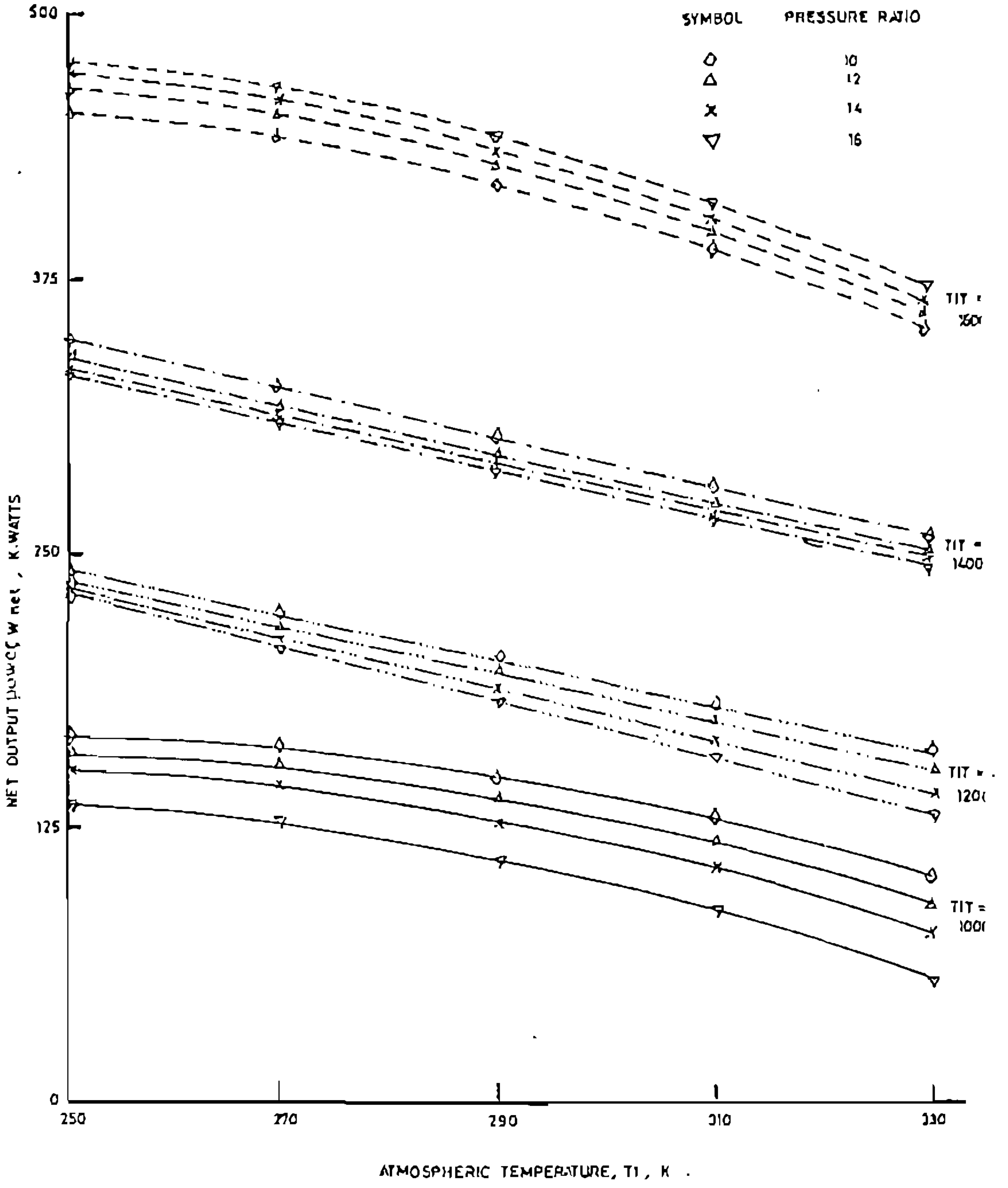


Figure. 2. Net output power with various maximum turbine inlet temperature (TIT).

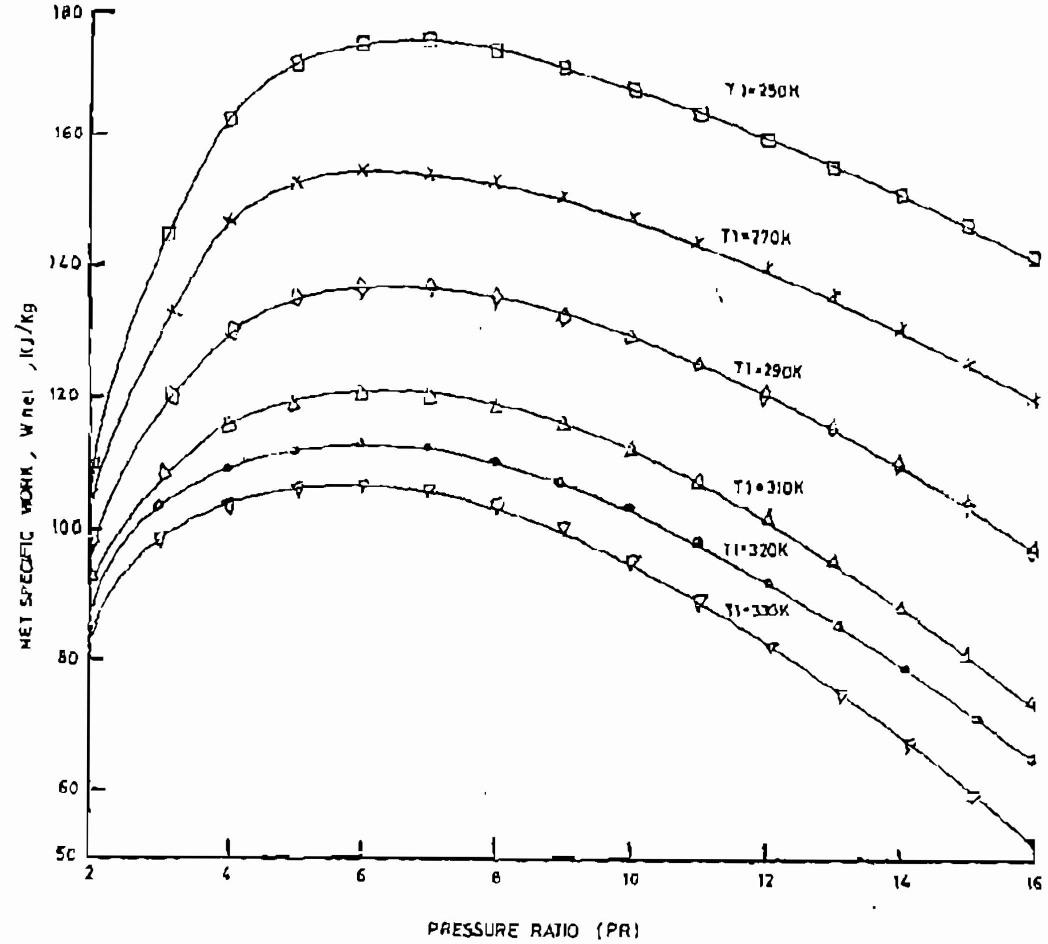


Figure. 3. Net specific work (W_{net}) with various atmospheric temperature and constant turbine inlet temperature (TIT = 1000 K)

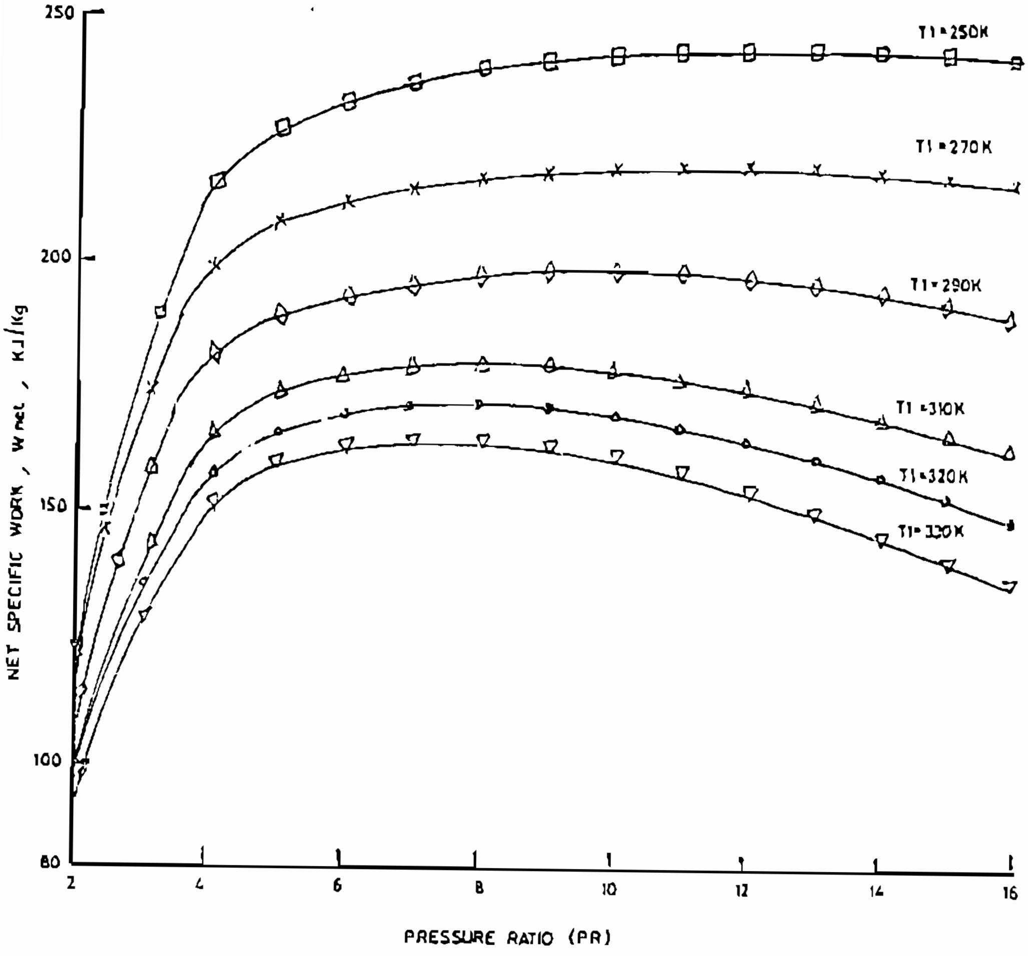


Figure. 4. Net specific work (W_{net}) with various atmospheric temperature, and constant turbine inlet temperature (TIT = 1200 K).

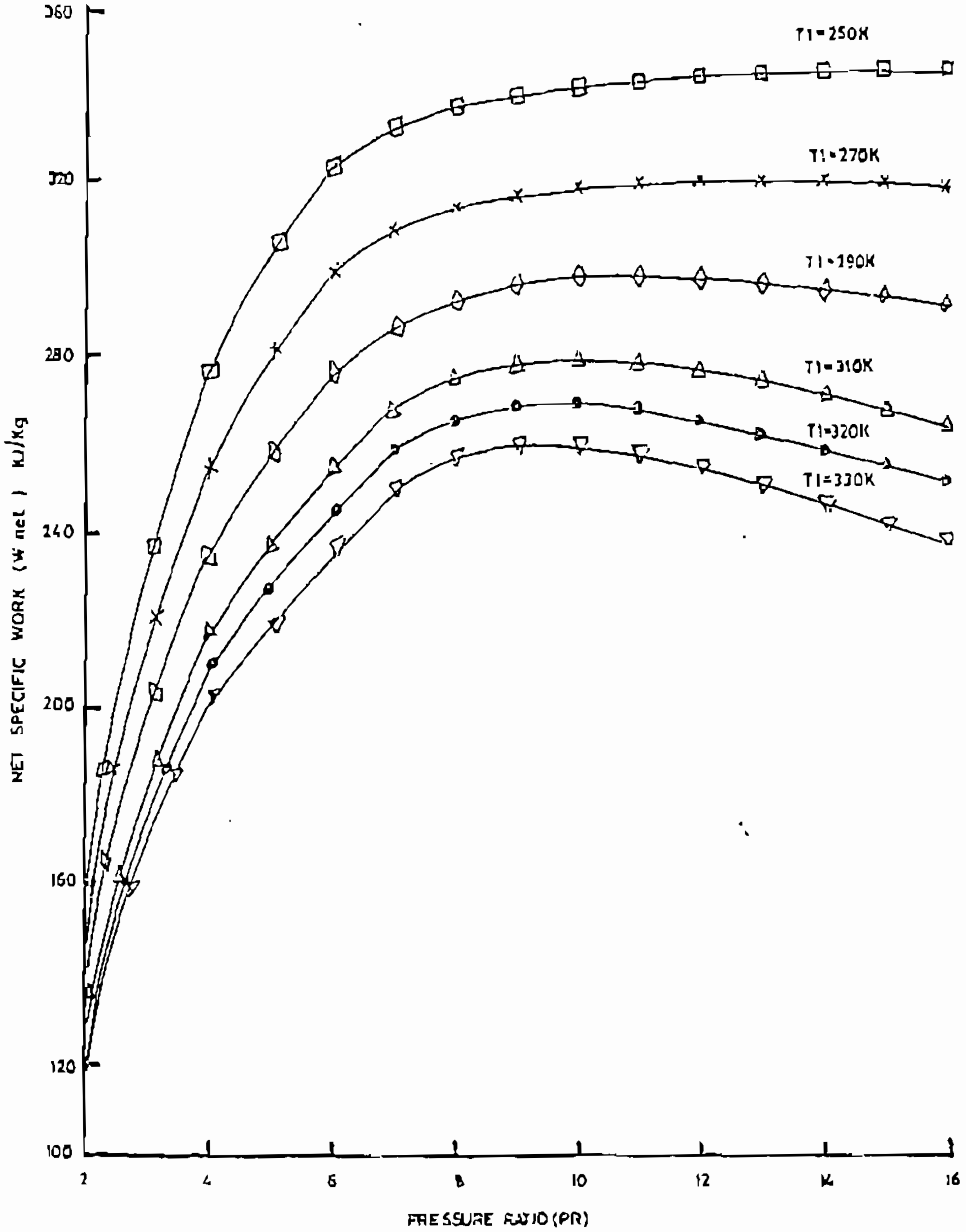


Figure. 5. Net specific work (W_{net}), with various atmospheric temperature and constant turbine inlet temperature (TIT = 1400 K).

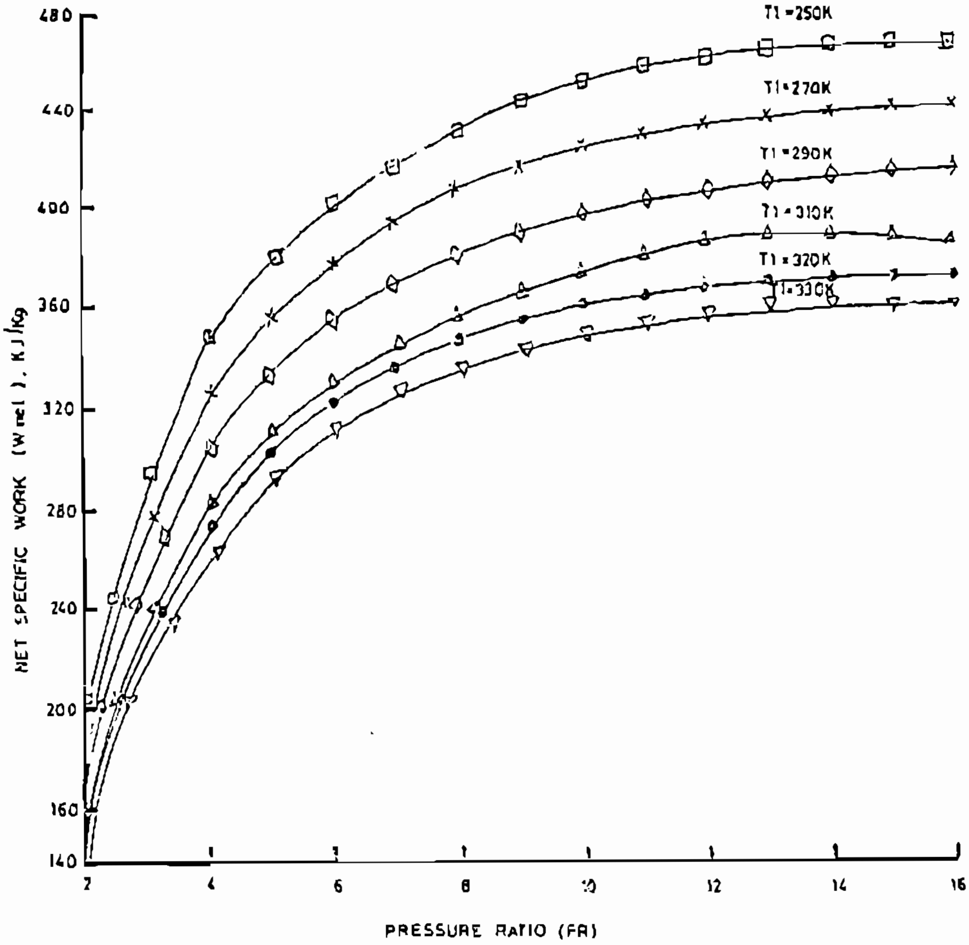


Figure. 6. Net specific work (W_{net}), with various atmospheric temperature and constant turbine inlet temperataure (TIT = 1600 K).

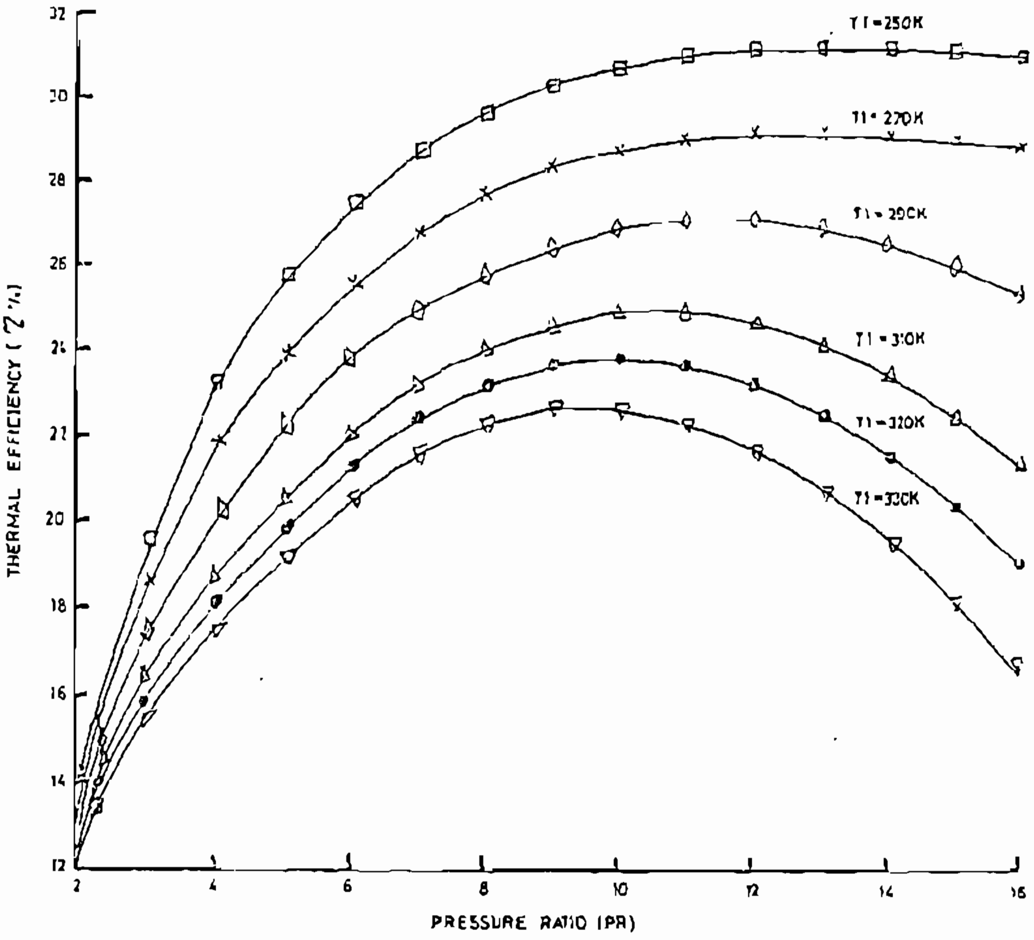


Figure. 7. Overall thermal efficiency with various atmospheric temperature, and constant turbine inlet temperature (TIT = 1000 K).

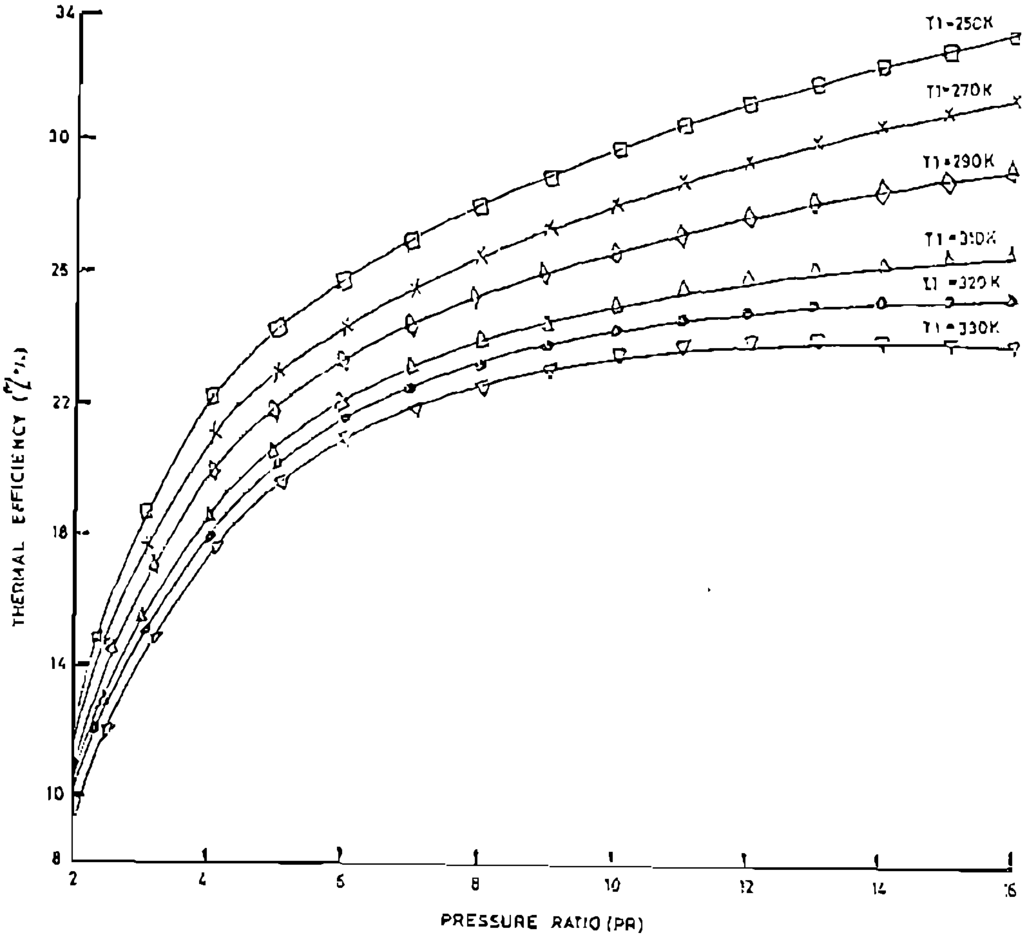


Figure. 8. Overall thermal efficiency with various atmospheric temperature, and constant turbine inlet temperature (TIT = 1200 K).

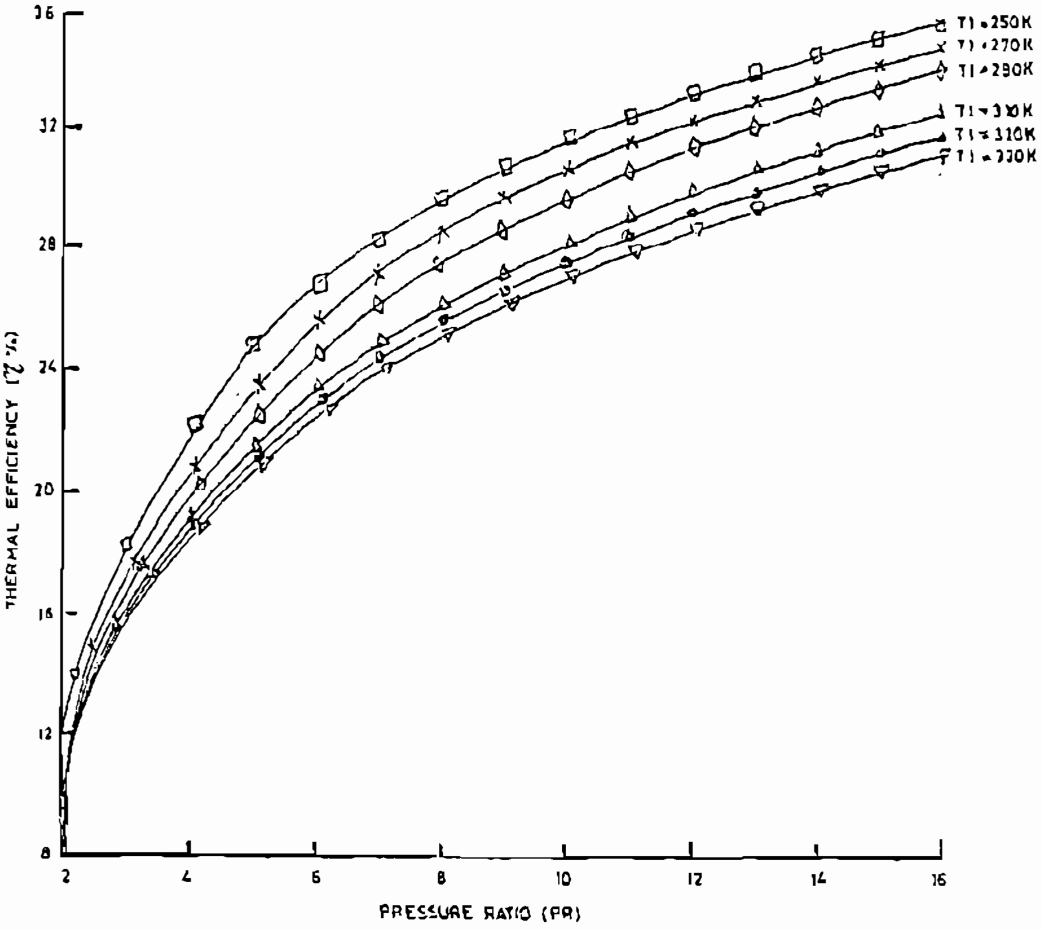


Figure. 9. Overall thermal efficiency with various atmospheric temperature, and constant turbine inlet temperature (TIT = 1400 K).

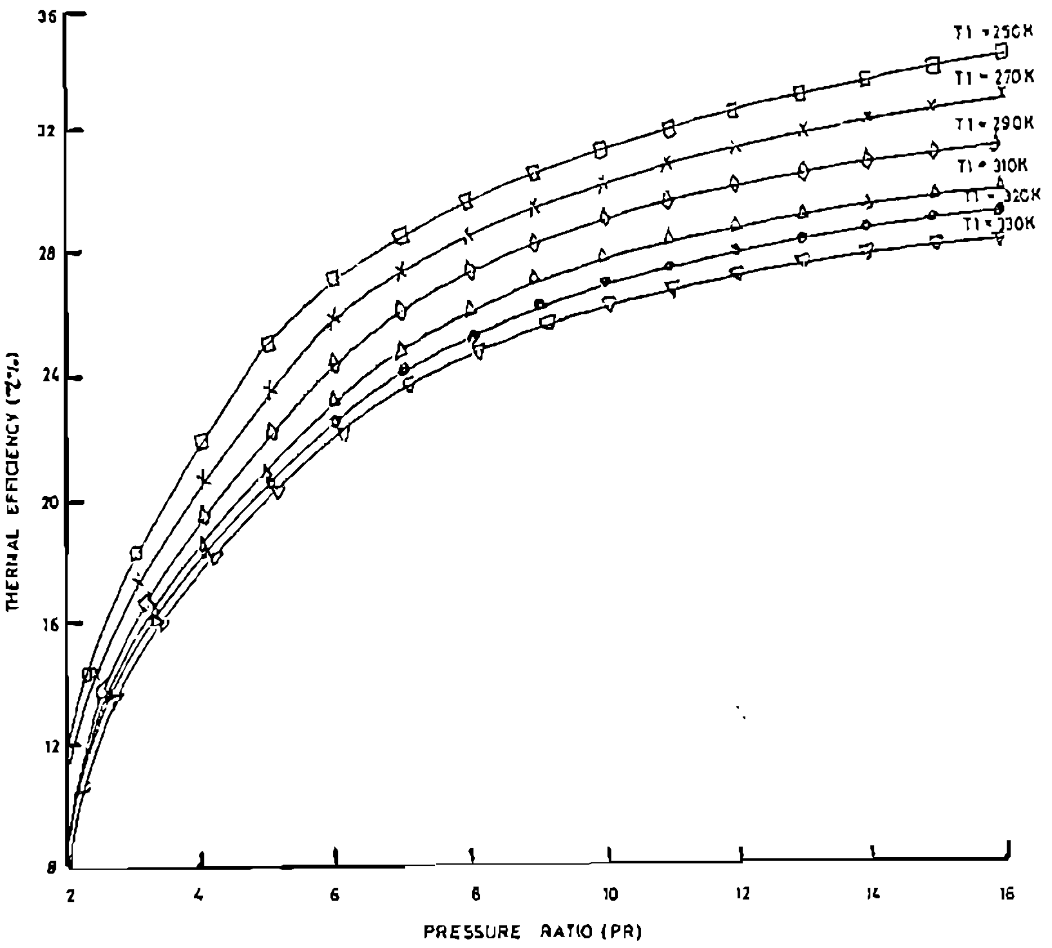


Figure. 10. Overall thermal efficiency with various atmospheric temperature, and constant turbine inlet temperature (TIT = 1600 K).

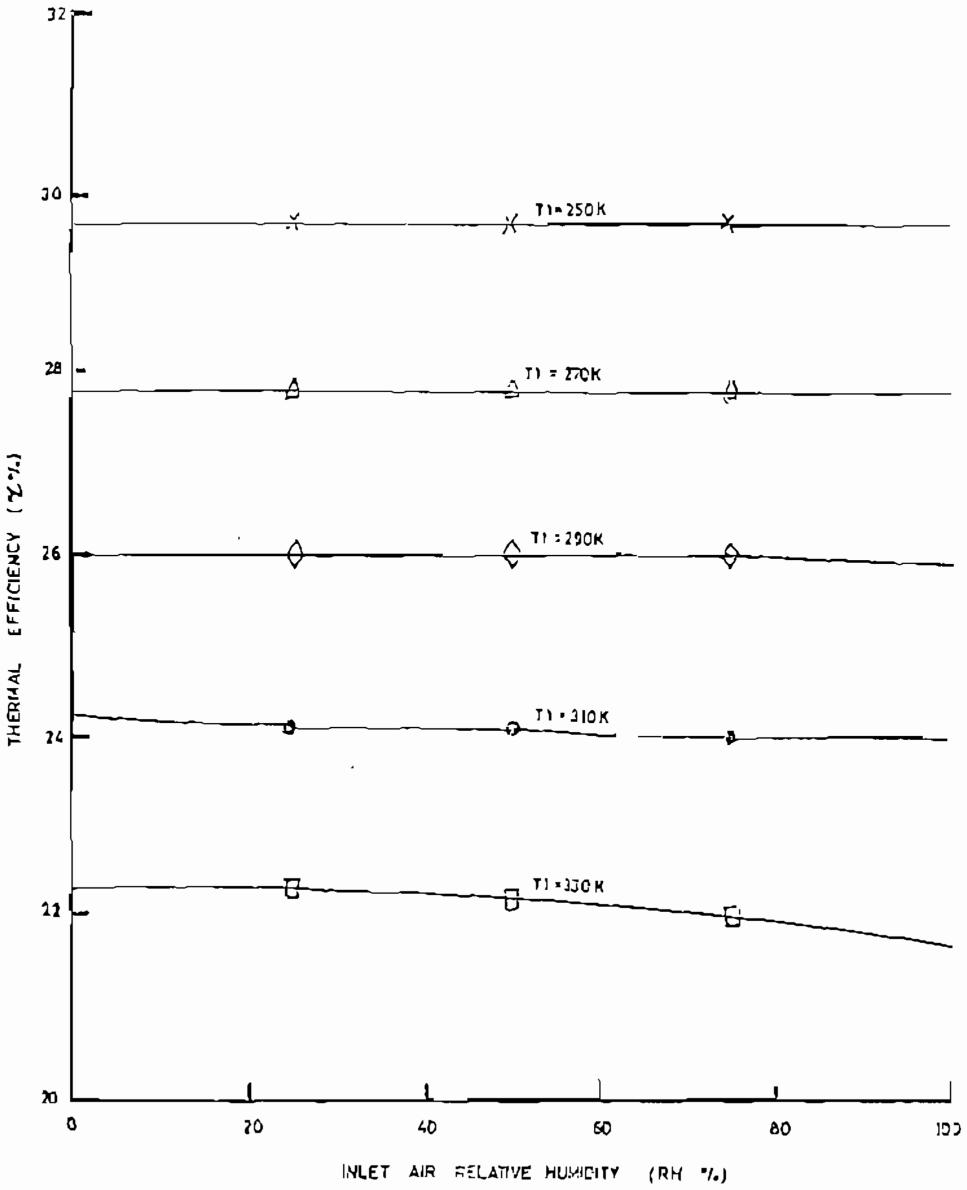


Figure. 11. Overall thermal efficiency with various atmospheric air temperature, and relative humidity, and at constant pressure ratio, (PR = 10) and constant turbine inlet temperature (TIT = 1200 K).

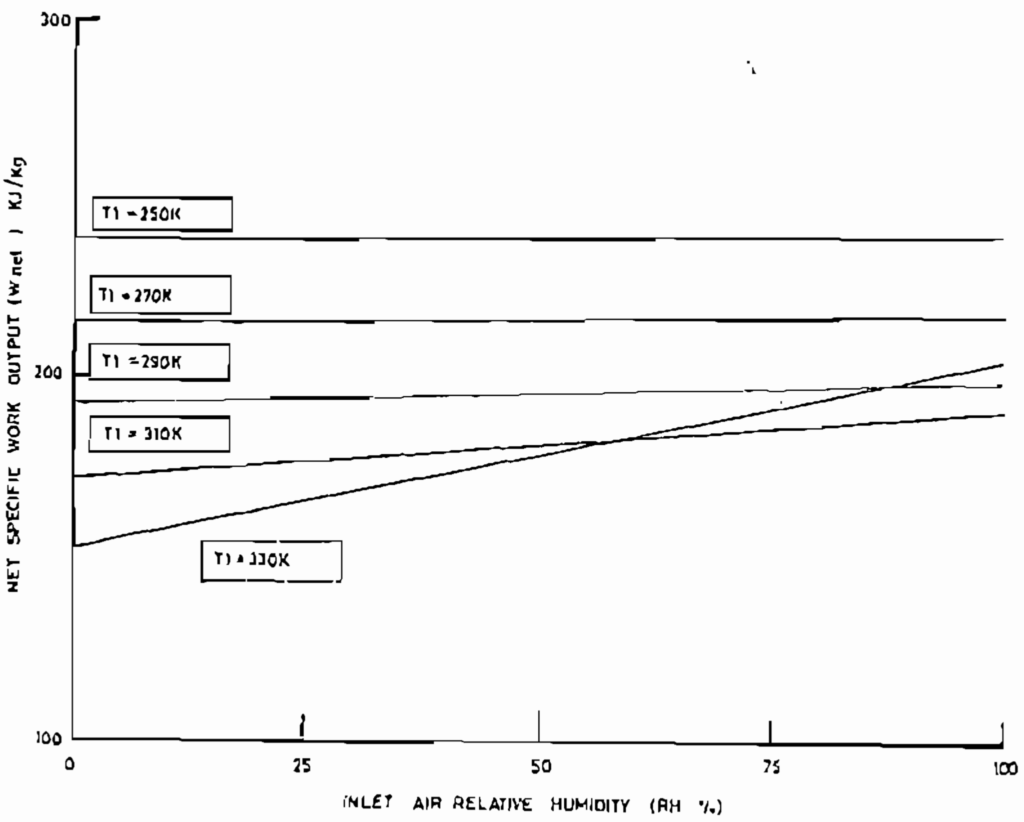


Figure. 12. net specific work (W_{net}) with various atmospheric air temperature, and relative humidity, and at constant pressure ratio (PR = 10) and constant turbine inlet temperature (TIT = 1200 K).

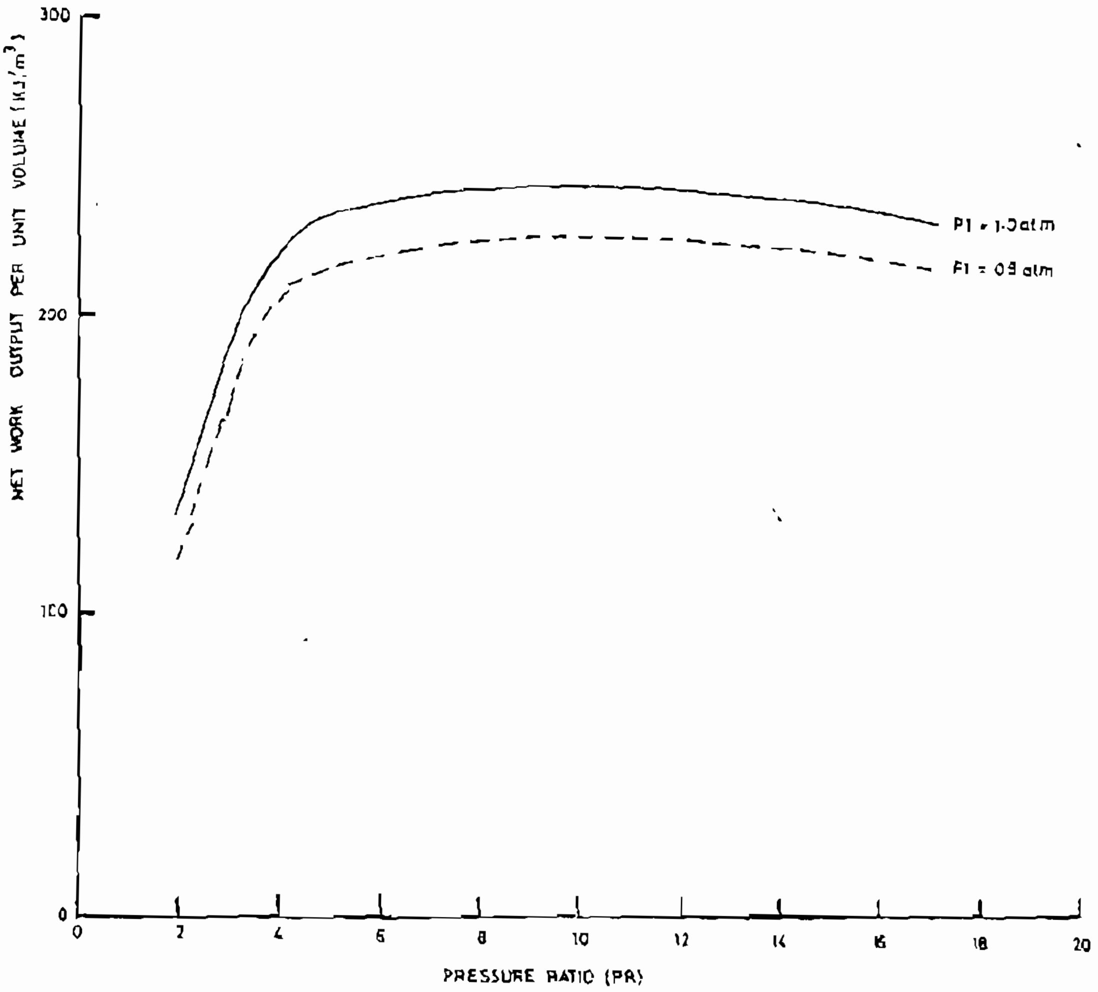


Figure. 13. Net work per unit volume with various pressure ratio, and at constant atmospheric temperature (T_1 = 280 K), and at constant inlet turbine temperature (TIT = 1200 K).

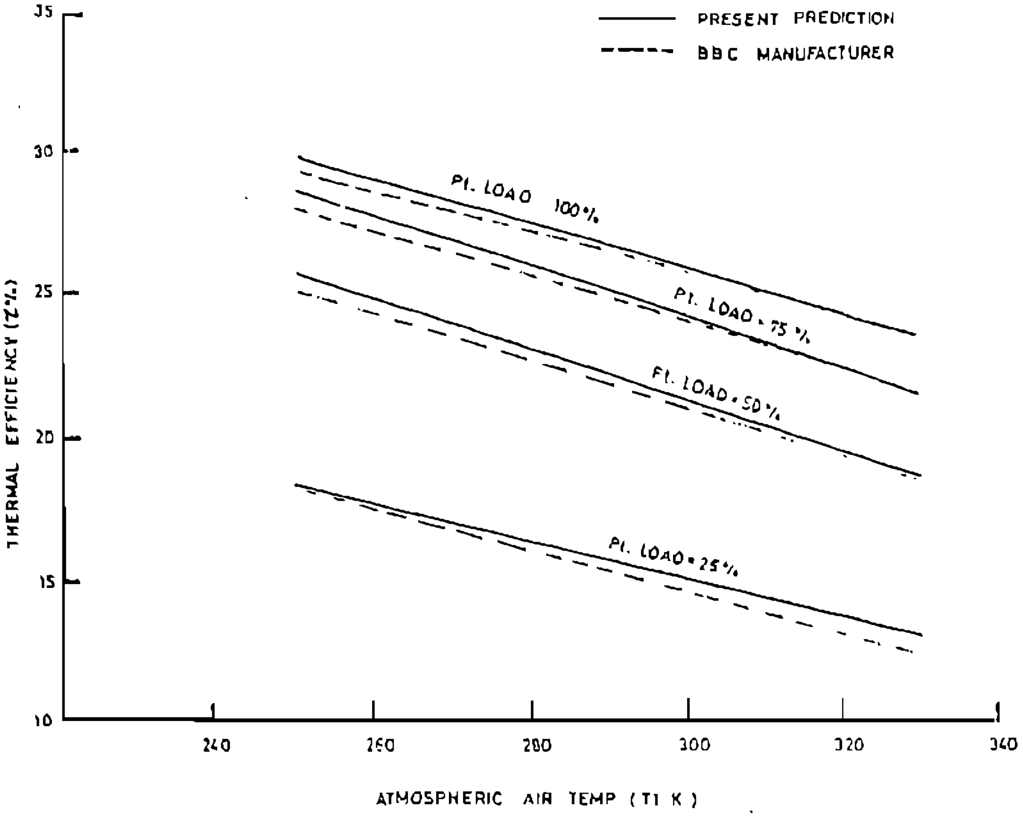


Figure 14. Overall thermal efficiency with various partial load, and at constant turbine inlet temperature (TIT = 1200K), and at constant pressure ratio (PR = 10).

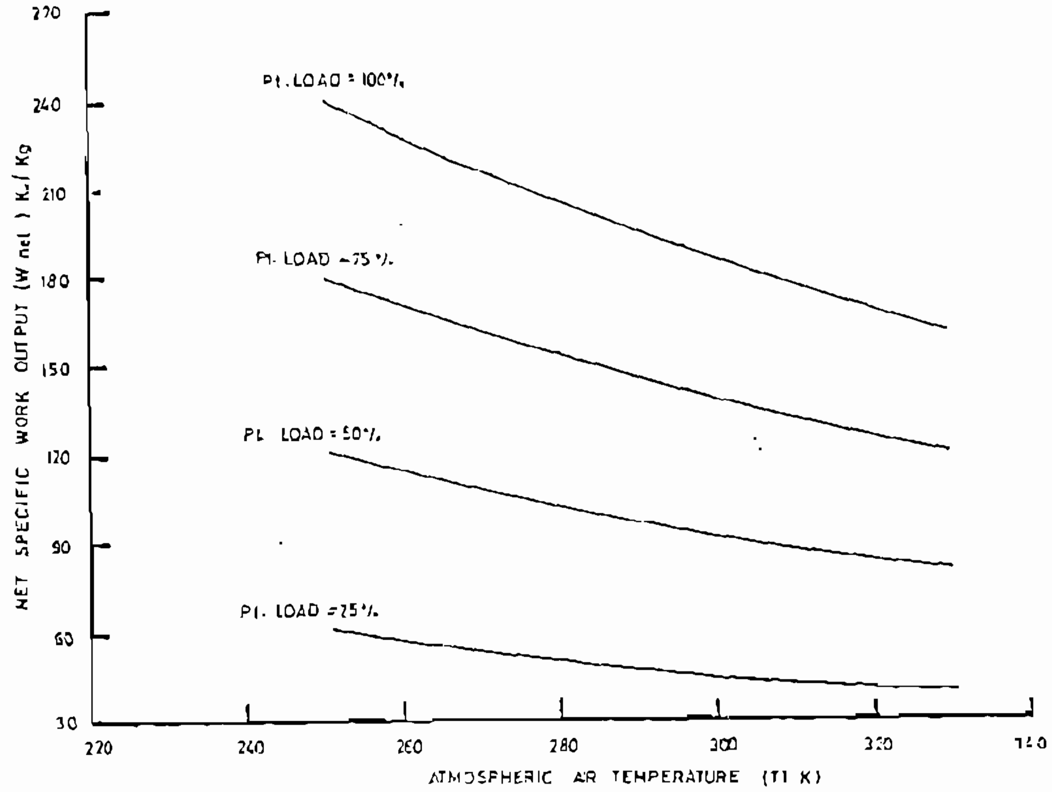


Figure. 15. Net specific work (W_{net}), with various partial load, and at constant turbine inlet temperature (TIT = 1200K), and pressure ratio (PR = 10).

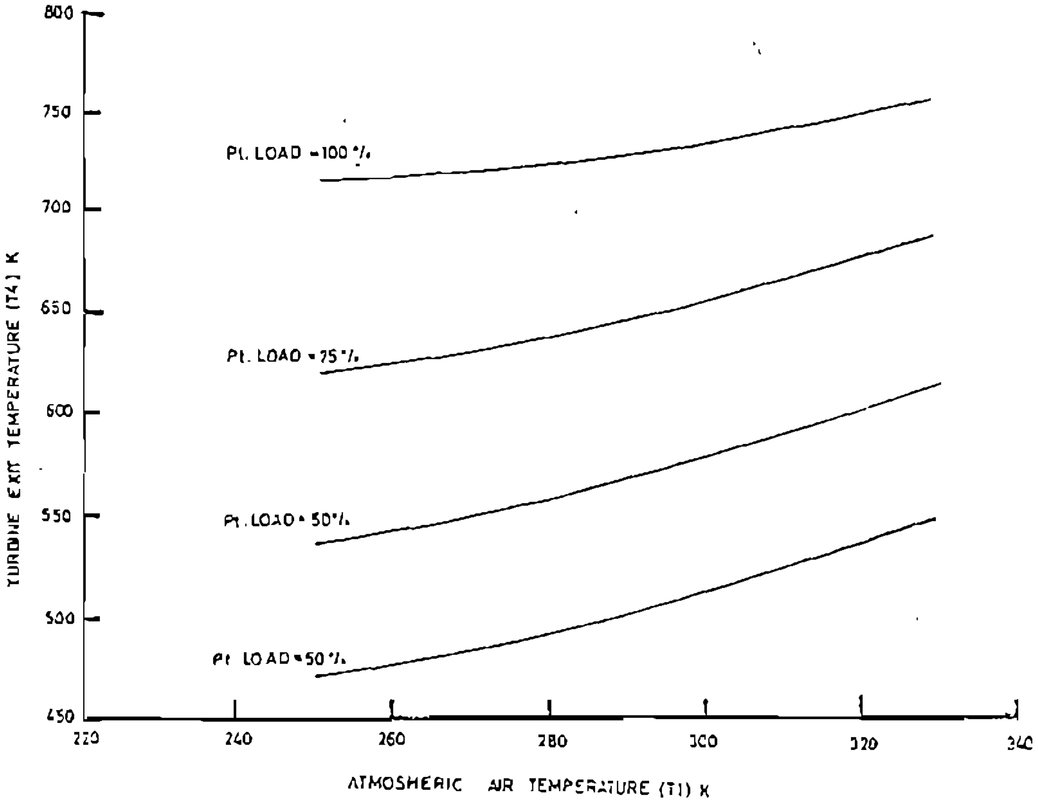


Figure. 16. Turbine exit temperature with various partial load, and at constant turbine inlet temperature (TIT = 1200K) and constant pressure ratio (PR = 10).