Comparison Researches on the Influences of Common Rail Pressures on the Diesel Engine's Sabah Cycle

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Abstract: *There are directly effects on diesel's Sabah cycle of common rail pressure, at the same time, the common rail pressure also affects the property indices: pre-expansion ratio, thermal efficiency, exergyefficiency and average valid pressure. It takes Weicai National VI diesel as an instance, describes the simplifies, basic presumptions and formulas of inner cylinder thermal process, and mainly designs and researches on the parameter indices of Sabah Cycle in different common rail pressure conditions.*

Keywords: Common Rail Pressure,Diesel Engine, Sabah Cycle

1. INTRODUCTION

This thesis takes Weicai National VI as a research target, this engine succeeds the primary one's features of advance technology, excellent function, high reliability, and may relay on moving to the higher exhaust standard. As shown in table 1 is the main technical parameters[1][2].

Table 1. *Common Rail Diesel Engine Technical Parameters*

Emission Level	**National 6**
Model	**Turbo & Middle Cooler, Electric Control High Pressure Common Rail**
Exhaust Volume	11.596*L*
Cylinder Diameter×Piston Travel	126×155*mm*
Rated Power	245*kW*
Rated Rotate Speed	1900*r/min*
Maximum Torque	1600*N·m*
Compress Ration	17：1
Ignite Order	1-5-3-6-2-4
Turbo Ratio	1.85：1

The compositions of high pressure common rail fuel injection system mainly includes[3][4][5]: oil supply pump, common rail tube, high pressure oil tube, fuel injectors, electronic control unit and various sensors;

Its basic working principle is as follow: The fuel supply pump conveys the fuel to the common rail, and an oil supply method that electrically separates the generation of the injection pressure from the injection process.

The common rail system high pressure oil pump mainly uses the CP3.3N-16/18 high pressure oil pump; The mechanical part and the actuator of high pressure common rail fuel injection system use the Bosch related spare part, the fuel injector is the CRIN2 type fuel injector, The electronic control unit uses EDC7, and the common rail uses LWRN3 common rail.

1.1 Basic Presumptions on the Calculations of Inner Cylinder Thermal Processes

For the establishment of inner cylinder combustion model, a quasi-dimensional model[1][6][7] has been adopted. Here is to explain: in the quasi-dimensional model, considering the non-uniformity in the cylinder, the fuel injection is divided into several small areas according to the empirical formula of non-uniform distribution of fuel air in the cylinder. Each small area is an independent one. The thermodynamic system also considers that the processes carried out in the relevant areas are all affected by the turbulent flow in the cylinder; the model is a process conceptualized by the diesel engine: fuel injection, spray crushing, mixture formation, heat release, heat transfer, and exhaust compositions.

1.2 Basic Formulasof Inner Cylinder Thermal Processes

Inner cylinder thermal processes in diesel engines are relatively complex, but there are always three parameters or (p, T, v) that represent the state of the gas in the cylinder; the process can be linked by energy, mass conservation equations, and equations of state.

(1) Basic Formula of Energy Conservation

According to the first theory of thermodynamics, established a formula of inner cylinder energy conservation:

$$\frac{d(mu)}{d\varphi} = -p \cdot \frac{dV_s}{d\varphi} + \frac{dQ_{Bm}}{d\varphi} - \sum \frac{dQ_{wi}}{d\varphi} - h_{ex} \cdot \frac{dm_{ex}}{d\varphi} \quad (1)$$

Among them: m -Inner cylinder working air quality, kg; u -Internal energy of inner cylinder air; p- Inner cylinder pressure, MPa; V_s -Cylinder working volume, L; Q_{Bm} -Heat absorption, kJ; Q_{wi} -Heat loss through the boundary of system, kJ; φ -Crank angel, $^{\circ}CA$; h_{ex} - Exhaust enthalpy from cylinder, kJ/kg ; $\frac{dm_{ex}}{d\varphi}$ -Exhaust flow rate from cylinder, $kg/^{\circ}CA$

(2) Formula of Mass Conservation

The amount of change in gas mass in a diesel engine cylinder is equal to the mass of fuel injected into the cylinder, the mass of gas flowing into the cylinder, and the mass of the gas flowing out of the cylinder, the formula is as below

$$\frac{dm}{d\varphi}=\frac{dm_{\beta}}{d\varphi}+\frac{dm_{s}}{d\varphi}-\frac{dm_{c}}{d\varphi} \tag{2}$$

Among them: m_{β} -Fuel mass injected into the cylinder, kg; m_s -Air mass flow into the cylinder, kg; m_e -Air mass flow out of the cylinder, *kg*

(3) Raw of Combustion and Heat Release

Utilizing Weber's combustion model as the engine cylinder heat release model for diesel engines, the empirical formulas for Weber's combustion are as below:

$$\frac{dx}{d\varphi}=\frac{\alpha}{\Delta\varphi_{c}}\cdot(m+1)\cdot y^{m}\cdot e^{-a\cdot y(m+1)} \tag{3}$$

$$dx=\frac{dQ_{Bm}}{Q_{Bm}} \tag{4}$$

$$y=\frac{\varphi-\varphi_{0}}{\Delta\varphi_{c}} \tag{5}$$

Among them: Q_{Bm} - Heat absorption, kJ; φ_0 - Combustion start, $^{\circ}CA$; $\Delta\varphi_c$ -Combustion duration, $^{\circ}CA$; *m*-Combustion quality index; α -weber parameter(α =6.9); φ -Crank angel, $^{\circ}CA$;

(4) Exergy and Exergy Efficiency

Heat Exergy in Heat Absorption Capacity Q_B :

$$e_{x,Q}=Q_{B}-a_{n,Q}=(1-\frac{T_{0}}{T_{1m}})Q_{B}=Q_{B}-T_{0}\Delta s_{1} \tag{6}$$

Average Temperature of Heat Absorption:

$$T_{1m}=\frac{Q_{B}}{\Delta s_{1}} \tag{7}$$

Exergy Efficiency:

$$\eta_{e_x}=\frac{w_{net}}{e_{x,Q}} \tag{8}$$

Among: $e_{x,Q}$ - Heat Exergy, *kJ/kg* ; $a_{n,Q}$ - Heat Anergy, *kJ/kg* ; T_{1m} - Average Temperature of Heat Absorption, *K*; Q_B - Cycle Heat Absorption Capacity, *kJ/kg* ; T_0 - Environment Temperature, *K*; Δs_1 - Entropy Increase during Heat Absorption Process, *kJ/(kg.K)*; w_{net} - Efficient Exergy(Cycle Work), *kJ/kg* ;

Exergy Loss:

$$i=T_{0}s_{g}=T_{0}(\Delta s_{2}+\Delta s_{0})=T_{0}(-\Delta s_{1}+\frac{Q_{2}}{T_{0}})=Q_{2}-a_{n,Q}=Q_{2}-T_{0}\Delta s_{1} \tag{9}$$

Among them: *i*-Exergy Loss, *kJ/kg* ; s_g -Entropy Generation, *kJ/(kg.K)* ; Δs_0 - Environment Entropy Increase during Exothermic Process, *kJ/(kg.K)* ; Q_2 - Cycle Heat Release, *kJ/kg* ; Δs_2 -Entropy Increase during Exothermic Process, *kJ/(kg.K)*

2. Comparison Researches on Sabah Cycles in Different Common Rail Pressures

The target of the exergy analysis of Sabah cycles in different rail conditions is Weicai National 6, as shown in figure 1, 2 are p-v figure and T-s figure of Sabah cycles.

There is a comment: under different rail pressures, the highest temperatures and pressures are different, however, The ideal air inlet and outlet temperatures are the same at 1 point: the air states at 1 point and 5 point in Figures 1 and 2 do not change with the rail pressure. As shown in table 2 is sabah cycle relative parameters.

Table 2 *Sabah Cycle Relative Parameters*

Sabah Cycle	Air intake temperature T_a	Air intake pressure p_a
Relative Parameters	27℃	1.85*bar*

Comments: Environment temperature T_0 is -3℃,No.-10 Diesel Oil, External Characteristics Rational Speed

Among them, the cycle average pressure is expressed as below:

$$\frac{p_t}{p_a}=\left(\frac{\eta_t Q_B}{c_V T_a}\right)\left(\frac{1}{\kappa-1}\right)\left(\frac{\varepsilon_c}{\varepsilon_c-1}\right) \quad \textbf{(10)}$$

Compress Ratio: ε_c =17 (11); Constant Entropy index: κ =1.4 (12); then, $c_V=0.718kJ/(kg\bullet K)$ (13)

$$c_p=1.005kJ/(kg\bullet K) \quad (14)$$

Table 3 *The Maximum Cycle Pressure Corresponding to Different Target Rail Pressures*

Sabah Cycle	I	II	III	IV
Target Rail Pressure	900*bar*	1200*bar*	1500*bar*	1700*bar*
Maximum Cycle pressure	128*bar*	140*bar*	160*bar*	170*bar*

Condition I: $p_3=p_4=128bar$ (15) ; constant pressure pre-expansion ratio $\rho=2$ (16)

1-2 constant entropy process, $T_2 v_2^{\kappa-1}=T_a v_a^{\kappa-1}$ (17), $T_2=T_a\varepsilon_c^{\kappa-1}$ (18) , thus T_2 =932K (19)

$p_2 v_2^{\kappa}=p_a v_a^{\kappa}$ (20) $p_2=p_a\varepsilon_c^{\kappa}$ (21) $p_2=97.7bar$ (22)

2-3 constant volume process, $\frac{p_3}{T_3}=\frac{p_2}{T_2}$ (23)

$T_3=1221K$ (24)

the highest temperature:

$$T_4=\rho\times T_3=2\times1221=2442K \quad (25)$$

Intake specific volume: $\frac{p_a v_a}{T_a}=R_g$ (26)

$$v_2=v_3=\frac{v_a}{\varepsilon_c}=0.0274m^3/kg \quad (27)$$

$$v_4=\rho\times v_3=0.0548m^3/kg \quad (28)$$

$$v_a=v_5=\frac{287\times300}{1.85\times10^5}=0.465m^3/kg \quad (29)$$

4-5 constant entropy process, $T_5 v_5^{\kappa-1}=T_4 v_4^{\kappa-1}$ (30)

T_5 =1038K (31)

Cycle heat absorption $\boldsymbol{Q_B}$

$$Q_{23}=c_V(T_3-T_2)=0.718(1221-932)=207.5kJ/kg \quad (32)$$

$$Q_{34}=c_p(T_4-T_3)=1.005(2442-1221)=1227kJ/kg \quad (33)$$

$$\boldsymbol{Q_B=Q_{23}+Q_{34}=207.5+1227=1434.5kJ/kg} \quad (34)$$

Cycle heat release:

$$Q_2=c_V(T_5-T_1)=0.718(1038-300)=530kJ/kg \quad (35)$$

Cycle thermal efficiency:

$$\eta_t=\frac{w_{net}}{Q_B}=\frac{Q_B-Q_2}{Q_B}=\frac{1434.5-530}{1434.5}=\frac{904.5}{1434.5}=63.05\% \quad (36)$$

Cycle average efficient pressure: through formula (10), $p_t=20.6bar$ (37)

Irreversible constant volume process 5-1, $\frac{p_5}{T_5}=\frac{p_a}{T_a}$ (38) $p_5=6.4bar$ (39)

Entropy Increase during Heat Absorption Process:

$$\Delta s_{24}=c_p\ln\frac{T_4}{T_2}-R_g\ln\frac{p_4}{p_2}=1.005\ln\left(\frac{2442}{932}\right)-0.287\ln\left(\frac{128}{97.7}\right)=0.891kJ/(kg\bullet K) \quad (40)$$

Heat Anergy in Heat Absorption Capacity: $a_{n,Q}=T_0\Delta s_{24}=270\times0.891=240.6kJ/kg$ (41)

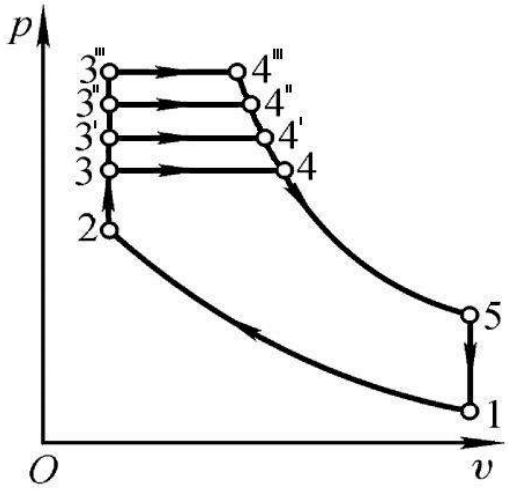
Heat Exergy in Heat Absorption Capacity: $e_{x,Q}=Q_B-a_{n,Q}=1434.5-240.6=1194kJ/kg$ (42)

Average Temperature of Heat Absorption: $T_{1m}=\frac{Q_B}{\Delta s_{24}}=\frac{1434.5}{0.891}=1610K$ (43)

Exergy Efficiency: $\boldsymbol{\eta_{e_x}=\frac{w_{net}}{e_{x,Q}}=\frac{904.5}{1194}=75.75\%}$ (44)

Exergy Loss:

$$i=T_0 s_g=Q_2-a_{n,Q}=530-240.6=289.4kJ/kg \quad (45)$$



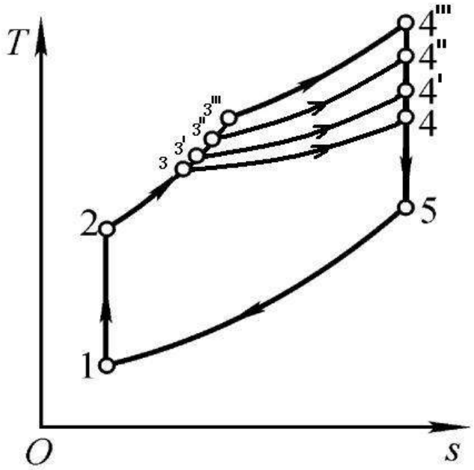


Figure1. Sabah Cycles p-v chart
Figure2. Sabah Cycles T-s chart

Condition II: $\boldsymbol{p_{3'} = p_{4'} = 140bar}$ (46)

The 1, 2, 5 points ideal air states are as the same as the results of condition I: The change of rail pressure in theoretical research content or experimental research content only involves and affects the heating process in the cylinder thermodynamic cycle, and doesn't involve any change in the exhaust system[8][9], below are the same.

4'-5 constant entropy process,

$p_{4'}v_{4'}^{\kappa} = p_5 v_5^{\kappa}$ (47) $v_{4'} = \sqrt[\kappa]{\frac{p_5}{p_{4'}}}v_5 = 0.0513m^3/kg$ (48)

$$v_{3'} = v_2 = \frac{v_a}{\varepsilon_c} = 0.0274m^3/kg \quad (49)$$

$$\rho' = \frac{v_{4'}}{v_{3'}} = 1.87 \quad (50)$$

2-3' constant volume process, $\frac{p_{3'}}{T_{3'}} = \frac{p_2}{T_2}$ (51)

$T_{3'} = 1335.5K$ (52)

3'-4' constant pressure process, $T_{4'} = \rho' \times T_{3'} = 2497K$ (53)

Thus,

$$Q_B{'}_{23'} = c_V(T_{3'} - T_2) = 0.718(1335.5 - 932) = 290kJ/kg \quad (54)$$

$$Q_B{'}_{3'4'} = c_p(T_{4'} - T_{3'}) = 1.005(2497 - 1335.5) = 1167kJ/kg \quad (55)$$

$$\boldsymbol{Q_B' = Q_B{'}_{23'} + Q_B{'}_{3'4'} = 290 + 1167 = 1457kJ/kg} \quad (56)$$

Cycle thermal efficiency: $\eta_t' = \frac{w_{net}'}{Q_B'} = \frac{Q_B' - Q_2}{Q_B'} = \frac{1457 - 530}{1457} = \frac{927}{1457} = 63.62\%$ (57)

Cycle average efficient pressure: through formula (10), $p_t' = 21.1bar$ (58)

Entropy Increase during Heat Absorption Process:

$$\Delta s_{24'} = c_p \ln\frac{T_{4'}}{T_2} - R_g \ln\frac{p_{4'}}{p_2} = 1.005\ln\left(\frac{2497}{932}\right) - 0.287\ln\left(\frac{140}{97.7}\right) = 0.887kJ/(kg \bullet K) \quad (59)$$

Heat Anergy in Heat Absorption Capacity: $a_{n,Q}' = T_0 \Delta s_{24'} = 270 \times 0.887 = 239.5kJ/kg$ (60)

Heat Exergy in Heat Absorption Capacity: $e_{x,Q}' = Q_B' - a_{n,Q}' = 1457 - 239.5 = 1218kJ/kg$ (61)

Average Temperature of Heat Absorption: $T_{1m}' = \frac{Q_B'}{\Delta s_{24'}} = \frac{1457}{0.887} = 1643K$ (62)

Exergy Efficiency: $\boldsymbol{\eta_{e_x}' = \frac{w_{net}'}{e_{x,Q}'} = \frac{927}{1218} = 76.11\%}$ (63)

Exergy Loss:

$$i' = T_0 s_g' = Q_2 - a_{n,Q}' = 530 - 239.5 = 290.5 kJ/kg \quad (64)$$

Condition III: $p_{3''} = p_{4''} = 160bar$ (65)

The 1, 2, 5 points ideal air states are as the same as the results of condition I,

4''-5 constant entropy process,

$$p_{4''} v_{4''}^{\kappa} = p_5 v_5^{\kappa} \quad (66) \qquad v_{4''} = \sqrt[\kappa]{\frac{p_5}{p_{4''}}} v_5 = 0.0467 m^3/kg \quad (67)$$

$$v_{3''} = v_2 = \frac{v_a}{\varepsilon_c} = 0.0274 m^3/kg \quad (68)$$

$$\rho'' = \frac{v_{4''}}{v_{3''}} = 1.70 \quad \mathbf{(69)}$$

2-3'' constant volume process, $\frac{p_{3''}}{T_{3''}} = \frac{p_2}{T_2}$ (70)

$T_{3''} = 1526K$ (71)

3''-4'' constant pressure process,

$T_{4''} = \rho'' \times T_{3''} = 2594K$ (72)

Thus,

$$Q_B''_{23''} = c_V (T_{3''} - T_2) = 0.718(1526 - 932) = 426 kJ/kg \quad (73)$$

$$Q_B''_{3''4''} = c_p (T_{4''} - T_{3''}) = 1.005(2594 - 1526) = 1073 kJ/kg \quad (74)$$

$$\mathbf{Q_B'' = Q_B''_{23''} + Q_B''_{3''4''} = 426 + 1073 = 1499 kJ/kg} \quad (75)$$

Cycle thermal efficiency:

$$\eta_t'' = \frac{w_{net}''}{Q_B''} = \frac{Q_B'' - Q_2}{Q_B''} = \frac{1499 - 530}{1499} = \frac{969}{1499} = 64.64\% \quad (76)$$

Cycle average efficient pressure: through formula (10),

$$p_t'' = 22.1 bar \quad (77)$$

Entropy Increase during Heat Absorption Process:

$$\Delta s_{24''} = c_p \ln \frac{T_{4''}}{T_2} - R_g \ln \frac{p_{4''}}{p_2} = 1.005 \ln\left(\frac{2594}{932}\right) - 0.287 \ln\left(\frac{160}{97.7}\right) = 0.887 kJ/(kg \bullet K) \quad (78)$$

Heat Anergy in Heat Absorption Capacity:

$$a_{n,Q}'' = T_0 \Delta s_{24''} = 270 \times 0.887 = 239.5 kJ/kg \quad (79)$$

Heat Exergy in Heat Absorption Capacity:

$$e_{x,Q}'' = Q_B'' - a_{n,Q}'' = 1499 - 239.5 = 1260 kJ/kg \quad (80)$$

Average Temperature of Heat Absorption:

$$T_{1m}'' = \frac{Q_B''}{\Delta s_{24''}} = \frac{1499}{0.887} = 1690K \quad (81)$$

Exergy Efficiency: $\boldsymbol{\eta_{e_x}'' = \frac{w_{net}''}{e_{x,Q}''} = \frac{969}{1260} = 76.90\%}$ (82)

Exergy Loss:

$$i'' = T_0 s_g'' = Q_2 - a_{n,Q}'' = 530 - 239.5 = 290.5 kJ/kg \quad (83)$$

Condition IV: $p_{3'''} = p_{4'''} = 170bar$ (84)

The 1, 2, 5 points ideal air states are as the same as the results of condition I,

4'''-5 constant entropy process,

$$p_{4'''} v_{4'''}^{\kappa} = p_5 v_5^{\kappa} \quad (85)$$

$$v_{4'''} = \sqrt[\kappa]{\frac{p_5}{p_{4'''}}} v_5 = 0.0447 m^3/kg \quad (86)$$

$$v_{3'''} = v_2 = \frac{v_a}{\varepsilon_c} = 0.0274 m^3/kg \quad (87) \qquad \rho''' = \frac{v_{4'''}}{v_{3'''}} = 1.63 \quad (88)$$

2-3''' constant volume process, $\frac{p_{3'''}}{T_{3'''}} = \frac{p_2}{T_2}$ (89)

$T_{3'''} = 1622K$ (90)

3'''-4''' constant pressure process,

$$T_{4'''} = \rho''' \times T_{3'''} = 2644K \quad (91)$$

Thus,

$$Q_B'''_{23'''} = c_V(T_{3'''} - T_2) = 0.718(1622 - 932) = 495kJ/kg \quad (92)$$

$$Q_B'''_{3'''4'''} = c_p(T_{4'''} - T_{3'''}) = 1.005(2644 - 1622) = 1027kJ/kg \quad (93)$$

$$\mathbf{Q_B''' = Q_B'''_{23'''} + Q_B'''_{3'''4'''} = 495 + 1027 = 1522kJ/kg} \quad (94)$$

Cycle thermal efficiency:

$$\eta_t''' = \frac{w_{net}'''}{Q_B'''} = \frac{Q_B''' - Q_2}{Q_B'''} = \frac{1522 - 530}{1522} = \frac{992}{1522} = 65.18\% \quad (95)$$

Cycle average efficient pressure: through formula (10),

$$p_t''' = 22.6bar \quad (96)$$

Entropy Increase during Heat Absorption Process:

$$\Delta s_{24'''} = c_p \ln\frac{T_{4'''}}{T_2} - R_g \ln\frac{p_{4'''}}{p_2} = 1.005\ln\left(\frac{2644}{932}\right) - 0.287\ln\left(\frac{170}{97.7}\right) = 0.889kJ/(kg \cdot K) \quad (97)$$

Heat Anergy in Heat Absorption Capacity:

$$a_{n,Q}''' = T_0 \Delta s_{24'''} = 270 \times 0.889 = 240.0kJ/kg \quad (98)$$

Heat Exergy in Heat Absorption Capacity:

$$e_{x,Q}''' = Q_B''' - a_{n,Q}''' = 1522 - 240.0 = 1282kJ/kg \quad (99)$$

Average Temperature of Heat Absorption:

$$T_{1m}''' = \frac{Q_B'''}{\Delta s_{24'''}} = \frac{1522}{0.889} = 1712K \quad (100)$$

Exergy Efficiency: $$\boldsymbol{\eta_{e_x}''' = \frac{w_{net}'''}{e_{x,Q}'''} = \frac{992}{1282} = 77.38\%} \quad (101)$$

Exergy Loss:

$$i''' = T_0 s_g''' = Q_2 - a_{n,Q}''' = 530 - 240.0 = 290.0kJ/kg \quad (102)$$

Table 4 is the comparison results among the 4 different rail pressure, the this table, it'll be able to discover that: with the rail pressure raise up, the cycle heat absorption Q_B , cycle thermal efficiency η_t, exergy efficiency η_{e_x}, cycle average efficient pressure p_t are increased, however, the constant pressure pre-expansion ratio ρ declined.

Table 4. *Comparison Results of Comparison among 4 rail pressures*

	I	II	III	IV
Q_B (kJ/kg)	1434.5	1457	1499	1522
ρ	2	1.87	1.70	1.63
η_t (%)	63.05	63.62	64.64	65.18
η_{e_x} (%)	75.75	76.11	76.90	77.38
p_t (bar)	20.6	21.1	22.1	22.6

Table 5 is exergy analysis comparison results of the Sabah cycles in different common rail pressures: with the rail pressure grows, the heat exergy in heat absorption, the average temperature of heat absorption and the exergy efficiency increase, however the exergy loss keeps in a stable range basically.

Table 5. *Exergy Analysis Comparison Results of the Sabah Cycles in Different Rail Conditions.*

Condition	$e_{x,Q}$ (kJ/kg)	T_{1m} (K)	η_{e_x} (%)	i (kJ/kg)
I	1194	1610	75.75	289.4
II	1218	1643	76.11	290.5
III	1260	1690	76.90	290.5
IV	1282	1712	77.38	290.0

3. Conclusions

This article established the basic formulas of the thermal process in the cylinder; compared with the data of cyclic heat absorption, cyclic heat efficiency, exergy efficiency, mean effective pressure, etc. of the Sabahcycle under the four different rail pressures of the common rail system, the comparison research results show that: The rail pressure increases, the circulating heat absorption, the cycle thermal efficiency, the exergy efficiency, and the average effective pressure, etc., have increased. For the constant pressure pre-expansion ratio, the Sabah cycle increases with the rail pressure and the constant pressure pre-expansion ratio Reduce.

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