PERFORMANCE IMPROVEMENT BY SPLITTING RANKINE CYCLE

S. De*, D. Roy and A. Bhattacharya
Department of Mechanical Engineering, Jadavpur University,
Kolkata-700032, India

Abstract Energy analysis is done to investigate the effects of 'splitting' a basic Rankine cycle. Higher number of splits is found to improve the performance of the cycle. Higher maximum pressure and temperature of steam from boiler improves the performance of the power cycle for same number of splits.

*Keywords**:** Split Rankine cycle, performance study*

INTRODUCTION

Joule-Brayton cycle (for gas power plants) and Rankine cycle (for steam power plants) have been considered so far as the most popular basic cycles for most of the power plants. Several modifications have been proposed on Rankine cycle to improve its performance either from energy or from exergy view point (Krejci et.al, 1992). Reheat cycle is introduced to obtain acceptable dryness fraction at the last stage of the turbine operating with high-pressure steam to avoid blade erosion. As a consequence, the specific power output increases and efficiency may increase or decrease depending on mean temperature of heat addition for reheat cycle. Regenerative feed heating, on the other hand, is acceptable as a suitable modification of basic Rankine cycle to improve the performance, though it occurs at the cost of specific power output. A direct contact type regenerative feed heater serves the purpose of deaeration of steam in addition.

Alternative combinations of several reheat and regenerative feed heating (with at least one deaeration) have been used for conventional steam power generation. Very few illustrations of a major international engineering activity better than the development of a 'combined power plants' are possible (Horlock, 1995). Steam cycle to be used as 'bottoming' cycle of a combined power plant, has to be different from that of previous conventional steam power plant (Foster-Pegg, 1976). As an example, feed water heating is not recommended, except for deaeration, for bottoming steam cycle in a combined power plant (Horlock, 1991), as it lowers the overall efficiency. It has been found that two or more (multi) pressure steam cycles are suitable for combined power plants in order to reduce irreversibility in the process of heat transfer from hot flue gas to water/steam in the heat recovery steam generator (Kehlhofer, 1991). Many a proposal has been made for such multi-pressure 'split-Rankine' cycles (Horlock, 1992). No detailed study, so far, has been reported on the necessity of 'splitting' a basic Rankine cycle into any arbitrary number of elemental cycles that results into a multi-pressure steam cycle. Investigation has been made to study influence of some design and operating parameters on the performance of a multi-pressure split Rankine cycle. Numerical computational method using computerized steam table has been adopted in this investigation to study the necessity of split in a basic Rankine cycle.

BASIC CONCEPTS AND THERMODYNAMIC MODEL

Simplified flow diagram and the corresponding T-s diagram have been shown in Fig 1a and 1b respectively. Arbitrary number of splits, in the basic Rankine cycle is assumed to study the effect. N number of 'splits' in the basic Rankine cycle yields N+1 number of steam turbines (ST) and pumps operating at different pressure levels. Exhaust steam from any of the turbines (except the lowest pressure one) is mixed with steam from the boiler for the next lower-pressure turbine. The boiler is assumed to generate steam at different pressures but at constant maximum temperature (T_{max}). The maximum pressure of steam generation is assumed 6000 kPa, 7000 k Pa or 8000 kPa and the condenser pressure is constant at 3.6 k Pa.

The isentropic efficiency of expansion in each steam turbine is assumed identical as 0.95. A little amount (about 3% of total) of steam from the exit of the last but one turbine is used for deaeration. The rest mass flow passes through the condenser (CN). Sub-cooling of 3^0C is assumed to happen in the condenser. Pressure is raised by feed pumps and these feed pumps distribute the mass flow in the boiler for corresponding steam turbines. The compression of liquid in the pumps is assumed to be isentropic. Pressure drop and heat loss are not taken into account for the sake of simplicity.

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*Email: de_sudipta@rediffmail.com

ANALYSIS

The total mass flow through all the turbines is assumed to be 1kg at steady state. The work output by the i-th turbine is:

$$(W_{ST})_i = (m_{ST})_i \times \{(h_{ST})_{in} - (h_{ST})_{exit}\}_i \qquad (1)$$

Where $(m_{ST})_i$ is the mass flow of steam through the i-th turbine and $(h_{ST})_{in}$ and $(h_{ST})_{exit}$ are the specific enthalpies at the inlet and exit of that turbine respectively.
Similarly, the work input for the i-th pump is estimated as:

$$(W_P)_i = (m_P)_i \times \{(h_P)_{exit} - (h_P)_{in}\}_i \qquad (2)$$

The total specific work output by all the steam turbines is:

$$w_{ST} = \sum_{i=1}^{N+1} (W_{ST})_i \qquad (3)$$

Where N is the number of splits in the basic Rankine cycle. Similarly, the total specific work input to all the pumps is:

$$w_P = \sum_{i=1}^{N+1} (W_P)_i \qquad (4)$$

The heat input to the boiler consisting of economiser, evaporator and superheater for the i-th stream of working fluid (water/stream) is:

$$(Q_B)_i = (m_B)_i \times \{(h_B)_{exit} - (h_B)_{in}\}_i \qquad (5)$$

Where $(m_B)_i$ is the mass flow of water/steam of the i-th stream through the boiler and $(h_B)_{exit}$ and $(h_B)_{in}$ are the specific enthalpies of working fluid at the exit and inlet of the boiler respectively.
It is obvious from Fig. 1a that:

$$\{(h_P)_{exit}\}_i = \{(h_B)_{in}\}_i \qquad (6)$$

The mixing of steam from the boiler with exhaust steam from the previous higher-pressure turbine is assumed adiabatic. Hence,

$$\{(h_{ST})_{in}\}_i = \frac{(m_{ST})_{i-1} \times \{(h_{ST})_{exit}\}_{i-1} + (m_B)_i \times \{(h_B)_{exit}\}_i}{(m_{ST})_{i-1} + (m_B)_i} \qquad (7)$$

Also, the total specific heat input to the boiler is:

$$q_B = \sum_{i=1}^{N+1} (Q_B)_i \qquad (8)$$

The efficiency of the cycle is:

$$\eta = \frac{w_{ST} - w_P}{q_B} \qquad (9)$$

The property values of steam are calculated by a comprehensive steam table developed on the basis of formulations involving Gibbs and Helmholtz functions. Successive bi-section method and Newton-Raphson iteration scheme are used to solve the steady state mass and energy conservation equations for each component.

RESULTS AND DISCUSSIONS

Net power output and efficiency of energy conversion are the parameters to indicate the performance of a power cycle. To determine the maximum possible values of these two quantities or a suitable optimum combination of them for best performance is the primary objective in studying thermodynamics of a power cycle. More power output, in combination with the maximization of cycle efficiency, is the ultimate goal of optimization. The operating parameters are to be determined to achieve this goal through thermodynamic analysis. However, after the thermodynamic analysis, the capital cost of achieving more power or higher efficiency has to be assessed and balanced against resulting savings.

The power cycle under consideration is a ‘split-Rankine’ steam power cycle with any arbitrary number of ‘splits’ resulting into a ‘multi-pressure’ cycle. Specific work output and overall efficiency are used as the performance criteria. The performance of the power cycle is investigated for variations of number of splits in the basic Rankine cycle. The total mass flow (i.e., 1kg) is assumed to be equally distributed among the streams of fluids in the boiler (i.e., economiser, evaporator and superheater). It is defined as the ‘reference value’ of mass flow for a given number of splits.

Figure 3 shows the variation of specific work output with number of splits (N) in the basic Rankine cycle for different T_{max} and p_{max}=7000 kPa. The work output of the steam cycle increases for the introduction of intermediate-pressure steam turbines (i.e., introducing more splits). The constant pressure lines diverge in the h-s diagram for steam with entropy increase. The mixing of exhaust steam from any previous higher-pressure turbine with steam from the next lower-pressure superheater is irreversible and is associated with increase in entropy. Therefore, the next lower-pressure turbine will deliver more work for the same pressure drop across it than that for the case of ‘without split’. The specific work output increases monotonically with higher number of splits as the same effect is more pronounced with more splits in the basic Rankine cycle. The specific work output increases with higher T_{max} for same number of splits (N) as shown in fig. 3. It is due to the fact that the overall enthalpy drop in the steam turbines increases for higher T_{max} for a given p_{max} (say 7000 kPa).

The increase in number of splits in basic Rankine cycle is found to increase the efficiency (Fig 4). With more intermediate splits, the required heat input to water/steam increases for given mass flow. However, the corresponding gain in specific work output (as shown in Fig.3) outweighs the increase in heat input and this leads to higher efficiency for more splits in the basic Rankine cycle. The effect of gain in efficiency by splitting the basic Rankine cycle is more pronounced for higher T_{max} for a given p_{max} (i.e.,7000 kPa). The mean temperature of heat addition increases with higher T_{max} for a given P_{max}. This is why the efficiency is more for same number of splits for higher T_{max}.

The same effects of number of splits on specific work and efficiency are shown in Figs 5 and 6 respectively for different p_{max} (say 6000 kPa, 7000 kPa and 8000 kPa) and at constant T_{max} (i.e., 798.15K). It is observed that higher p_{max} is desired for a given N for better specific work and efficiency. This is because higher p_{max} for a given T_{max} increases the overall enthalpy drop in turbines as well as mean temperature of heat addition. However, this may simultaneously decrease the dryness fraction of steam at the lowest pressure turbine, which must be more than 0.85 to avoid blade erosion. The advantage of a gain in efficiency and power output with more splits has to be investigated in detail with respect to capital cost and complexity of the plant to ascertain the feasibility in actual practice.

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CONCLUSIONS

Performance study of a multi-pressure split Rankine cycle employing numerical computation of property values of steam has been carried out. The effects of number of splits in a basic Rankine cycle on the specific work output and efficiency for different maximum pressures and temperatures of steam from boiler are studied. It is observed that higher number of splits in a given basic Rankine cycle will increase specific work as well as efficiency. Higher maximum pressure and temperature of steam from the boiler will also improve the performance of the cycle.

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NOMENCLATURE

h	specific enthalpy, kJ/kg
m	mass flow, kg
N	number of splits in the Rankine cycle
p	pressure, kPa
Q	heat input, kJ
q	specific heat input, kJ/kg
s	specific entropy, kJ/kgK
T	temperature, K
W	work, kJ
w	specific work, kJ/kg
η	efficiency of power cycle

subscripts

B	boiler
CN	condenser
exit	at the exit
i	i-th stream of water/steam in the boiler
in	at the inlet
max	maximum
net	net work output
P	pump
ST	steam turbine

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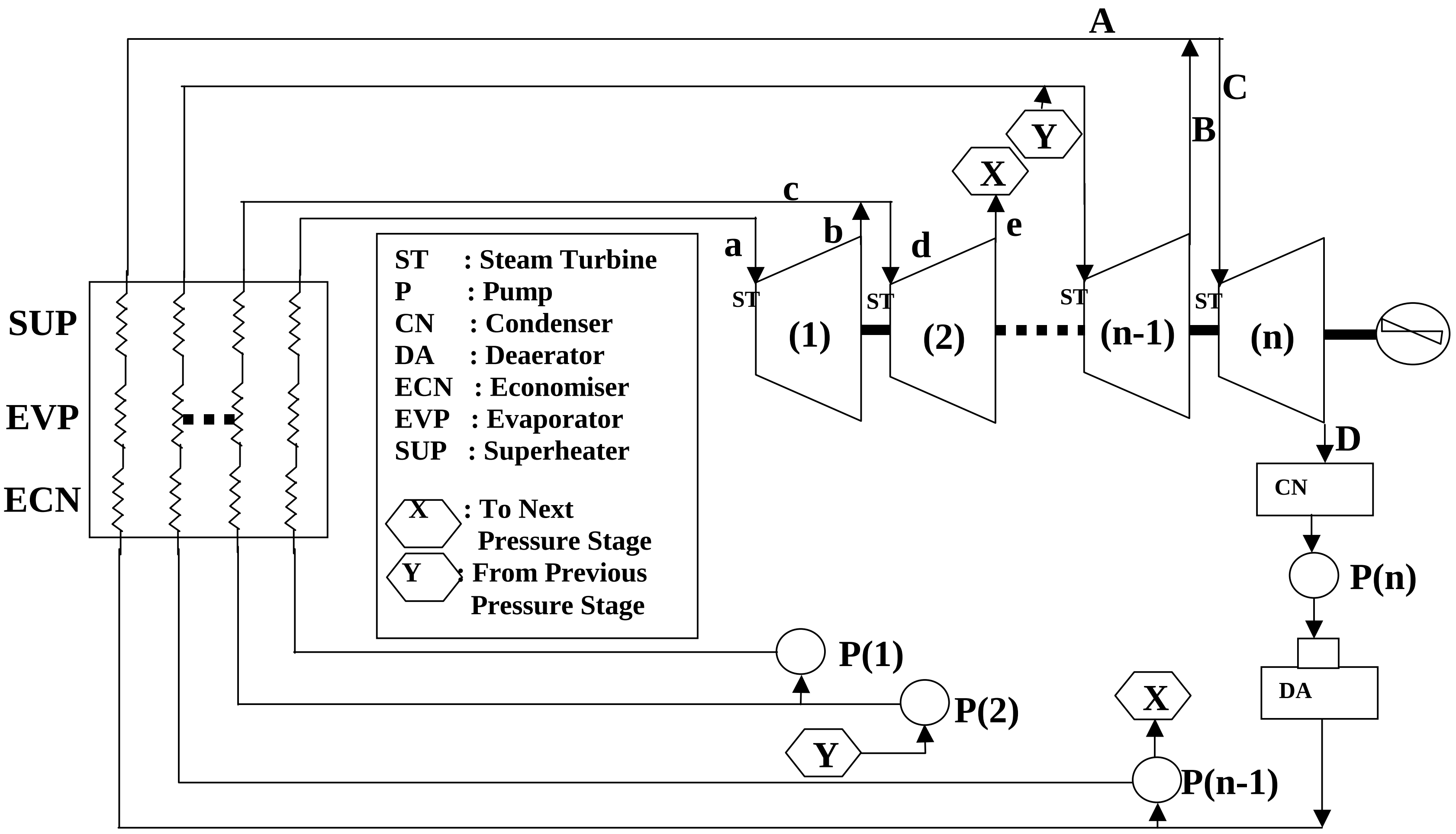

Fig. 1a : Schematic diagram of the Split Rankine cycle

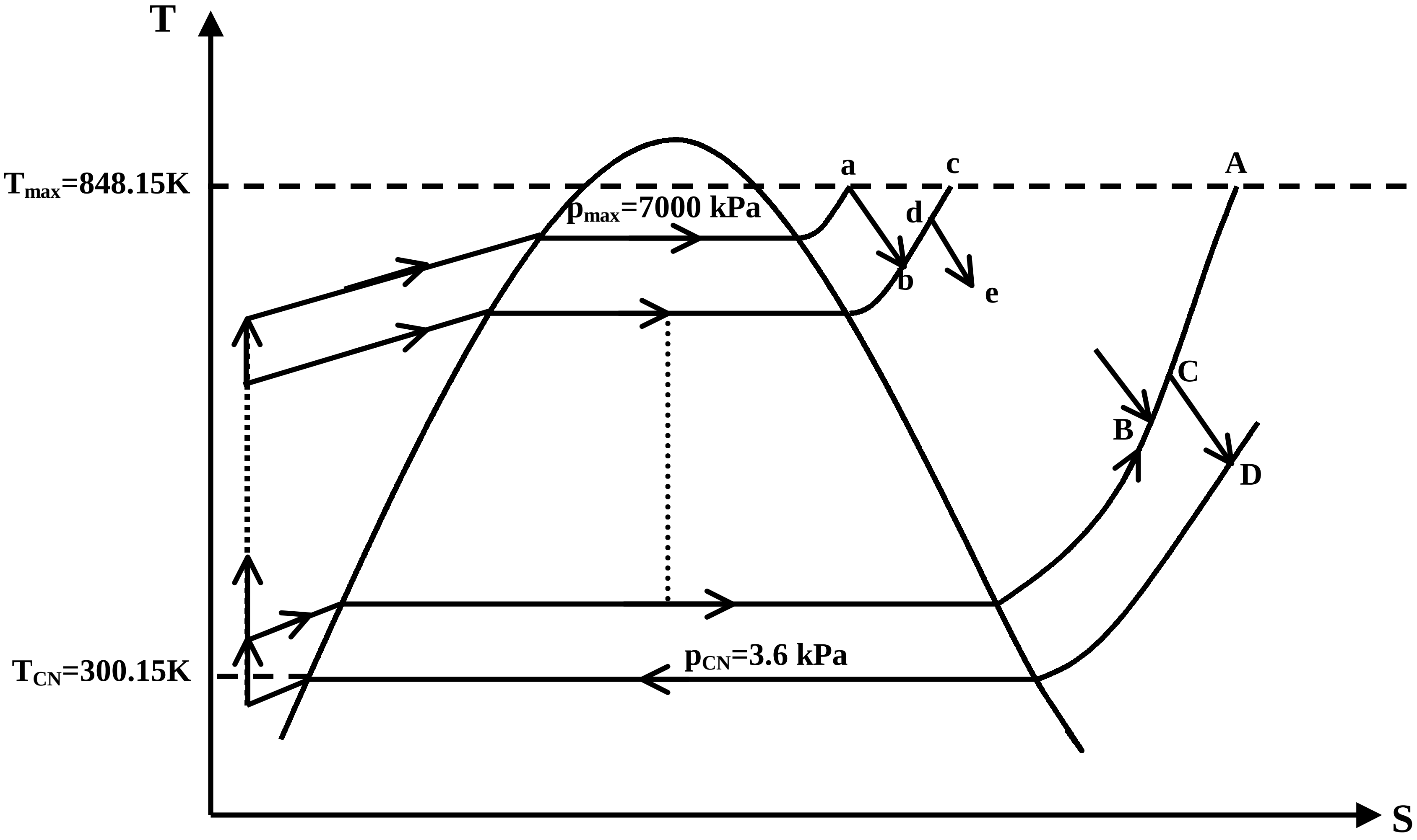

Fig. 1b : T-S diagram of the Split Rankine cycle

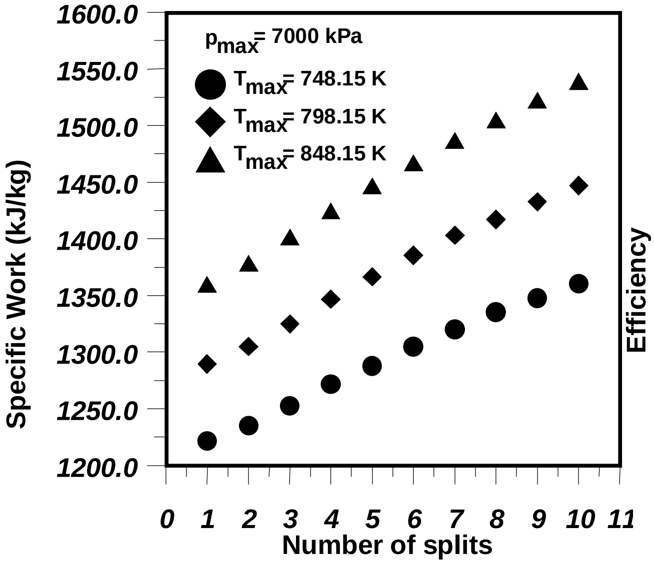

Fig.3: Effect of N on specific work for different T_{max}

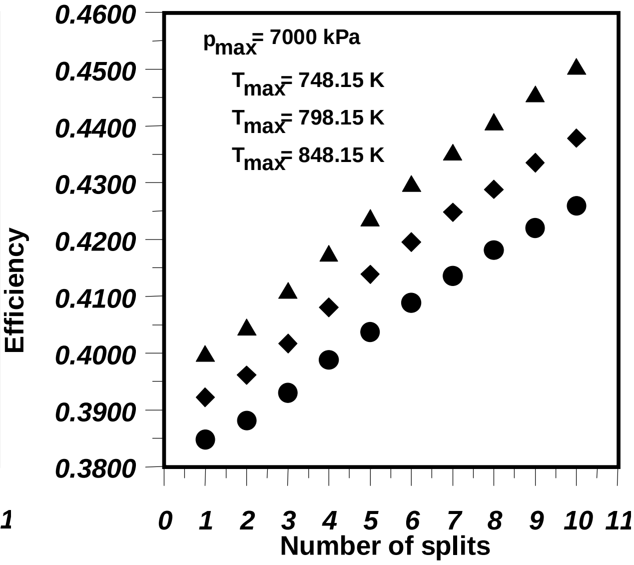

Fig.4: Effect of N on efficiency for different T_{max}

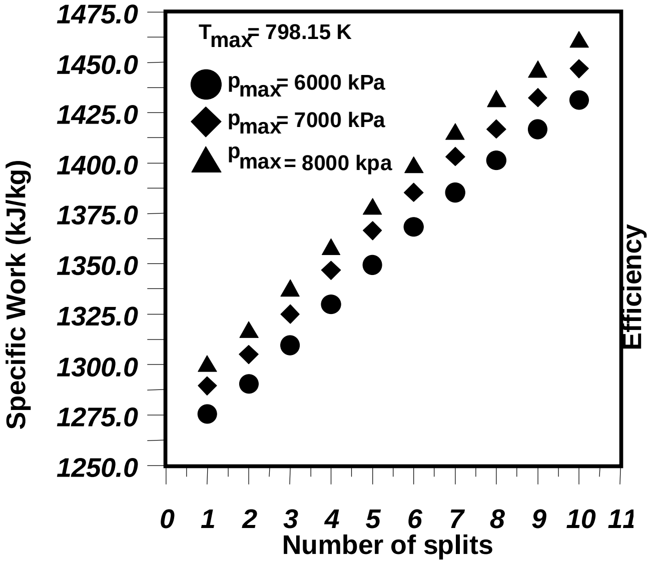

Fig.5: Effect of N on specific work for different p_{max}

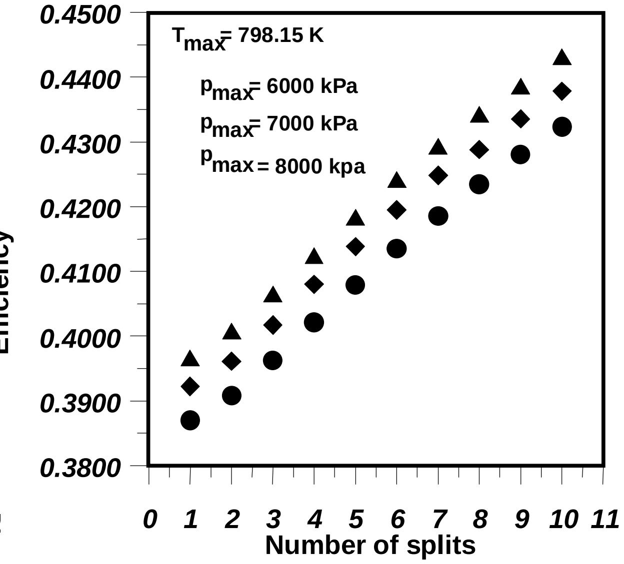

Fig.6: Effect of N on efficiency for different p_{max}