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# Gas turbine with heating during the expansion in the stator blades

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ABSTRACT

Reheat is used in the gas turbine to achieve higher power output. However, the reheat process is constrained by the heat quantity given to it and the choice of reheat point. Consequently, this paper introduces a new gas turbine cycle to overcome the reheat drawbacks and having superior features. In this cycle, the reheat process is replaced by processes of heating the expanded gases while passing through different turbine stator blades. Small amount of combusted gases is utilized to flow inside such blades for heating and mixing with the expanded gases. Nevertheless, this is performed with precautions of turbine overheating by reducing significantly the maximum temperature of the present cycle. The simulated results demonstrate that the cycle performance is increased by raising the quantity of heating during the expansion. Additionally, this cycle achieves greater efficient output than the traditional reheat Brayton cycle operating with higher maximum cycle temperature. To boost the present cycle efficiency, regeneration is used making the possibility of such cycle to be competitive to the combined cycle.



## 1. Introduction

Many researches have been performed to investigate the gas turbine cycle where a special focus is done to increase the cycle work by raising the maximum cycle temperature using blade cooling [1] or utilizing different blade alloys [2]. Reheating is one of the common methods used to step up the output power of gas turbine. Subsequently, it has been investigated intensively by many researchers [3–8]. It is very recognizable that the reheat process is constrained by the heat quantity given to it and the choice of reheat point. Utilizing reheat results in high exhaust temperature and that is considered as a waste thermal energy as well as it participates in the cycle efficiency reduction. Therefore, regeneration [9,10] and combined cycle [4,11–16] are solutions to increase the cycle efficiency. The humid air turbine was studied by [17] for cycle performance improvement. Additionally, Binary Brayton cycle [18–20], and Brayton cycle with the isothermal [21,22] represent two promising steps for gas turbine enhancement where the combination of their concept has been introduced in [23]. Even several trends have been introduced; reheat is still investigated due to its significance in gas turbines.

In the present paper, the main objective is to introduce a new gas turbine cycle with higher output and efficiency compared with the reheat cycle. This new cycle is performed by replacing the reheat process done outside the turbine by internal processes of heating during the expansion in different stator blade rows. The privilege of heating during the expansion, HDE, is to increase the cycle area. Furthermore, this process increases the flow kinetic energy of the expanded gases that can be used when the gases continue expanding in the rotor blades. In order to avoid turbine overheating, the maximum cycle temperature is remarkably reduced. This makes the temperature of the heated gases far below the overheating limit. Due to high exhaust temperatures, regeneration is utilized to boost the efficiency. Comparison is done with reheat cycle aiming to represent the present cycle merits.

## 2. System layout

Figs. 1 and 2 show the system layout and the cycle $T$–$s$ diagram. The system is composed of compressor, regenerative heater, combustion, turbine and heating units. Foremost, air enters the compressor at state point 1 and is compressed to state 2. The flow temperature is increased in the regenerative heater leaving it and entering the combustor at state 3. The flow leaves the combustor at state 4. The combusted gases are divided into two parts nominated by the heated main flow and the heating flow. The heating flow is used to heat the heated main flow. The processes of the heating flow while passing through heaters are drawn in Fig. 2 which dash lines in order to differentiate between these processes and the processes of the main flow. The main flow enters the turbine at state 4 and exits at temperature 5. For the main flow, subsequent expansions with heating in the stator blade rows end to points; a, c and e where the temperature and the kinetic energy are increased. On the other side, expansions in rotor blade rows are done isentropically and terminates at states b, d and 5 for the first, second and third stages, respectively. Still the flow temperature at state 5 is so high. Therefore, the flow passes through the

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**Nomenclature**

| | |
|---|---|
| $A_r$ | area ratio that equals the area at the stator inlet to that at the stator exit (–) |
| $C_p$ | specific heat at constant pressure (kJ/kg K) |
| $c$ | sound velocity (m/s) |
| $h$ | enthalpy (kJ/kg) |
| $k$ | ratio of the heat quantity given to the fluid and the enthalpy difference for heating during the expansion process (–) |
| KE | kinetic energy (kJ/kg) |
| $M$ | Mach number (–) |
| $m_r$ | the mass ratio of the heating flow to the heated flow (–) |
| $P$ | pressure (kN/m$^2$) |
| $q_{\mathrm{HDE}}$ | heat needed for heating during the expansion process (kJ/kg K) |
| $q_{\mathrm{in}}$ | heat transferred to the system (kJ/kg K) |
| $q_{\mathrm{tot}}$ | total heat transferred to the cycle (kJ/kg K) |
| $R$ | gas constant (kJ/kg K) |
| $T$ | temperature (K) |
| $T_8$ | maximum cycle temperature (K) |
| $T_r$ | temperature ratio that equals to the temperature at the stator row flow exit to that at the inlet (–) |
| $T_x$ | temperature of the heating flow leaving the first passage (K) |
| $v$ | flow velocity (m/s) |
| $w_c$ | compressor work (kJ/kg) |
| $w_{\mathrm{cy}}$ | cycle work (kJ/kg) |
| $w_{\mathrm{out}}$ | work produced by the system (kJ/kg) |
| $w_t$ | turbine work (kJ/kg) |

*Symbols*

| | |
|---|---|
| $\Delta$ | difference (–) |
| $\Delta p_r$ | pressure drop ratio; the ratio of the pressure drop in the rotor blades to that of the stage (–) |
| $\varepsilon$ | regenerative heater effectiveness (–) |
| $\gamma$ | specific heat ratio (–) |
| $\eta$ | cycle efficiency (–) |
| $\eta_{\mathrm{st}}$ | small stage efficiency (–) |
| $\vartheta$ | specific volume (m$^3$/kg) |
| $\pi$ | pressure ratio (–) |
| $\sigma$ | percentage of the heating quantity supplied by the first heating passage to that supplied by all passages of the blade (–) |

*Subscript*

| | |
|---|---|
| 1 | compressor inlet condition |
| 2 | compressor outlet condition |
| 3 | combustor inlet condition |
| 4 | combustor outlet condition |
| 5 | turbine outlet |
| $a$ | outlet condition of the first stator rows |
| $c$ | outlet condition of the second stator rows |
| $e$ | outlet condition of the third stator rows |
| ex | exit condition |
| id | ideal condition |
| in | inlet condition |
| st | stator blade row |
| $w$ | state without heating |

*Abbreviation*

| | |
|---|---|
| HDE | heating during the expansion |

regenerative heater and exhausted at point 6 to the atmosphere where the exhaust may be used for cogeneration. Instead of passing to the regenerative heater, the exhaust could be used to operate a bottoming cycle. However, selecting the regenerative heater in this work is to focus on the present cycle and to demonstrate its operation.

Back to the heating flow, a flow control valve is used to regulate the heating flow that enters the heating unit at state 7. The heating flow represents few percentages of the main flow. After the flow enters the first heating unit at state 7, some fuel is injected to raise the flow temperature to state 8 that is slightly higher than that of the main flow. The heating flow enters the first chamber that is attached to the first stator blade row. Thereafter, the heating flow passes inside the stator blades through internal passages to heat the main flow. A portion of the heating flow is injected into the heated main flow through stator blade holes, while the other portion enters the second heating unit at state 9. Some fuel is injected into the heating flow and raising its temperature till reaching state 10. For the third heating unit, the heating flow is specified by the process 11 and 12. After the heating flow passes through the third

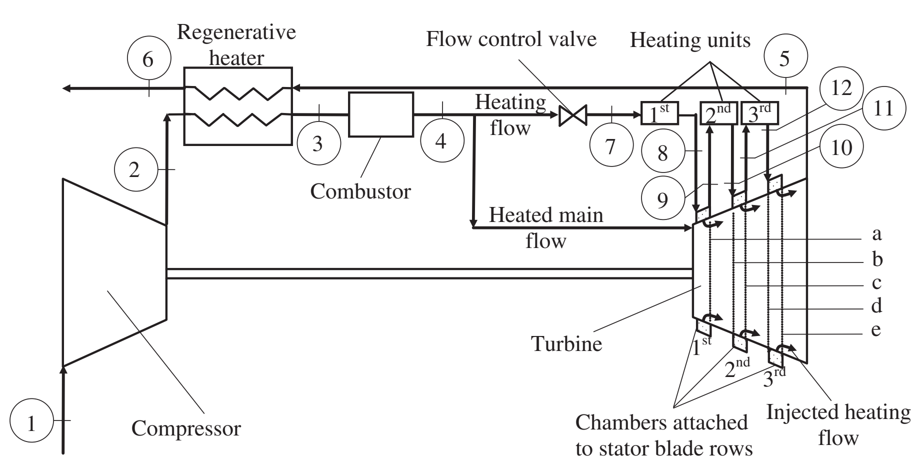


**Fig. 1.** Layout of the present cycle.