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Energy and Exergy Analysis on a Waste Heat Recovery Module for Helicopters

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ABSTRACT The exhaust of turboshaft engines contains a big amount of waste heat but does not provide propulsion power to the helicopter. Reusing the heat can increase fuel efficiency and reduce carbon emissions of the engine. This paper implements energy analyses and weight penalty estimations to a waste heat recovery module of the turboshaft engine. The components are a fuel preheating process and a power generation unit based on the organic Rankine cycle (ORC). The fuel penalty of the module consists of the fuel consumption of the following: carrying the instruments, overcoming the additional drag, and powering from the engine. Considering the high-temperature situation, working fluid of the module is chosen from benzene, R365mfc, and R245fa. The exergetic efficiency model has been validated using data from the Makila 1A1 turboshaft engine. Simulation based on a different engine, the T700 turboshaft engine, and a complete flight mission validate the energy efficiency improvement produced by the module. Results show that the module having existing technologies of the expander always cost additional fuel while increasing energy efficiency for the helicopter, but negative fuel penalties can be achieved by increasing the power-to-weight ratio of the module larger than 5.5. This research is trying to develop the field of application of ORC-based power units to a new sector of helicopters.

INDEX TERMS Waste heat, thermal analysis, energy efficiency, fuel economy.

I. INTRODUCTION

Nowadays, the aero-industry has a compelling demand to improve specific fuel consumption (SFC), reduce emissions, and decrease life cycle cost [1]. According to European Union's Clean Sky program, a 15% fuel consumption reduction is expected from helicopters [2]. To increase fuel and energy efficiencies while emitting less CO_2 and NOx, waste heat recovery is one of the most promising research directions [3], [4].

Having a global view of the onboard energy usage is necessary to heat recovery [5], [6]. The significant benefit of improving engine power conversion efficiency can be achieved by warming up the fuel and inlet air [7]. It has been proved that using the fuel as the heat sink can cool the electronic cabin while warming the fuel with a reasonable weight penalty to large helicopters [8], [9]. For small helicopters, the fuel or inlet air can be pre-warmed by the exhaust heat [2].

The exhaust gas of turboshaft engines does not provide power, so it can be used as the heat source of a recuperator, which can preheat compressor discharge air before it enters the combustion chamber [10], [11]. Zhang *et al.* [12] compared the tubular and primary surface recuperators of turboshaft engines by calculating their efficiencies of converting the exhaust heat. The results showed that an average 85% effectiveness between improved fuel economy and unfavorable parasitic weight can be achieved by using a primary surface recuperator. However, a small temperature difference between the exhaust gas and the inlet air will still result in a negative effect against it [3].

Another heat recovery option is to convert the waste heat of exhaust gas to electric power generation systems and satisfy the growing demand for onboard power [3], [13]. Organic Rankine cycle (ORC) is one of the most optimistic technologies for waste heat recovery in many industries due to its advantages of simple mechanism, high recovery efficiency, and easy maintenance [14], [15]. But the industrial applications which recover low-temperature heat from a large amount of steam by huge equipment can not install on helicopters because of weight cost [16], [17]. Moreover, the high-temperature exhaust gas of turboshaft engine may cause thermal decomposition issues to common refrigerant [18].

Recently, the possibility of mounting ORC-based waste heat recovery on helicopters is lifted by studies about small

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scale ORCs for high temperature waste heat recovery. The main focuses are high power density expanders [19], [20], high expansion ratio turbines [21], [22], bladeless turbines [19], working fluid options [9], [23] and so on. Liu *et al.* [24] used the exhaust gas of the auxiliary power unit (APU) as the heating source of an ORC-based waste heat recovery module to produce 12 kW electricity with an efficiency of 11% for the airborne equipment. Uusitalo *et al.* [21] examined a 10 kW and high expansion ratio ORC using Siloxane MDM for high temperature heat recovery. The results illustrated the importance of raising the isentropic efficiency of turbogenerator to reach higher power outputs. Song *et al.* [19] conducted efficiency predictions of the ORC system with Tesla turbine as the expander. Though using R245ca can lead to a higher efficiency than using R600, the output power and thermal efficiency are still lower than other relatively mature ORC applications. Sun *et al.* [9] investigated R245fa, R123, and their mixtures for small scale ORCs and got the maximum power output when the mass fraction of R245fa is 0.25. Nevertheless, they combined an air-cooling turbine with the ORC to construct a power and cooling system for hypersonic aircraft [25]. Baldi *et al.* [26] illustrated that ORCs using benzene and cyclohexane got the most annually fuel saving of ships, R245fa and R236ea performed worse than the high-temperature fluids. However, restrictions considered by the above studies are mainly temperature and investment cost, weight cost is barely mentioned. For installing these technologies in vehicles, especially flight ones, trade-off between the weight cost and the efficiency benefit is important and essential [27]. Therefore, the method for estimating the weight penalty caused by waste heat recovery technologies is needed.

In this paper, energy analyses will be carried out on a waste heat recovery module of helicopters constructed by a fuel preheating process and an ORC-based power generation unit (PGU). The waste heat of the equipment cabin is absorbed through the onboard oil loop to preheat the fuel and to improve the combustion efficiency; the waste heat of the exhaust gas is recovered through ORC to provide additional electric power [28]. To give a further look into the effect of the module, both the first and the second thermodynamic analyses are carried out, and fuel penalty is used to describe the weight penalty of the module.

The second section will introduce the waste heat recovery module. The third section is dedicated to the energy analysis and weight penalty models of the proposed system. The fourth section will verify the proposed models by a Makila 1A1 engine and give a further investigation into the T700-701D turboshaft engine concerning the power-to-weight ratio of PGU and working conditions of the helicopter.

II. INTEGRATED WASTE HEAT RECOVERY MODULE OF HELICOPTERS

An integrated waste heat system with the turboshaft as a core is illustrated in Fig. 1. Three units are connected in series: a fuel-based heat sink system [6], [29], a turboshaft, and an ORC-based PGU [9], [24].

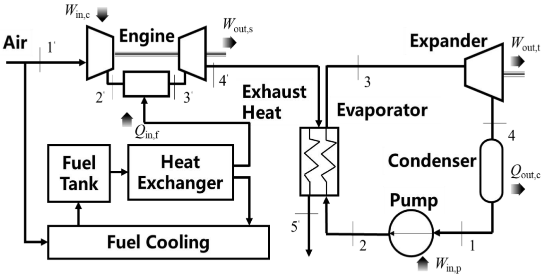

FIGURE 1. Configuration of the waste heat recovery module of helicopters.

To improve the combustion efficiency, the fuel is preheated by the electronic system, hydraulic system, and so on [6], [29]. After flowing out of the fuel tank, it first passes through the fuel/lubricating and fuel/hydraulic oil heat exchanger to absorb the heat [6]. Then, one part of the preheated fuel flows into the engine combustion chamber and the other part will be cooled by the air/fuel heat exchanger before returning to the fuel tank.

The exhaust gas of a conventional turboshaft carries and dissipates a big amount of heat into the environment [11]. In this module, a PGU is installed after the turboshaft through an evaporator, where part of the exhaust heat will exchange to the organic working fluid and convert into steam under equal pressure (point 2 to 3). The steam enters the expander to drive the turbine by adiabatic expansion (point 3 to 4) and leaves with a lower temperature and pressure, thus generating power from waste [22], [30]. The outlet of the expander passes through a condenser for heat release (point 4 to 1). Then it is adiabatically pressurized by the pump (point 1 to 2) and driven to the evaporator to join the next cycle.

III. METHODOLOGY

A. FIRST LAW OF THERMODYNAMICS AND ENERGY ANALYSIS

The integrated waste heat recovery module is combined with a Brayton cycle and a Rankine cycle. The T-S diagram of the combined power cycle is shown in Fig. 2. All numbers correspond to the characteristic points in Fig. 1. The dash lines between 1' and 2', 3' and 4' represent the ideal thermal entropy relation [31]. In practice, more work enters the compressor and less work out from the turbine because of irreversibility. Hence, the T-S relations are as 1'-2' and 3'-4'.

The first-law efficiency of the combined power cycle is [32]

$$\eta_Q = \frac{w_{net}}{q_{in}} \tag{1}$$

where w_{net} represents the network output, kJ/kg, and q_{in} the total heat input, kJ/kg, with the reference mass of fuel. They can be calculated as follows

$$w_{net} = (w_{out,t} - w_{in,c})_{eng} + (w_{out,t} - w_{in,p})_{PGU} \tag{2}$$

$$q_{in} = q_{in,f} \tag{3}$$

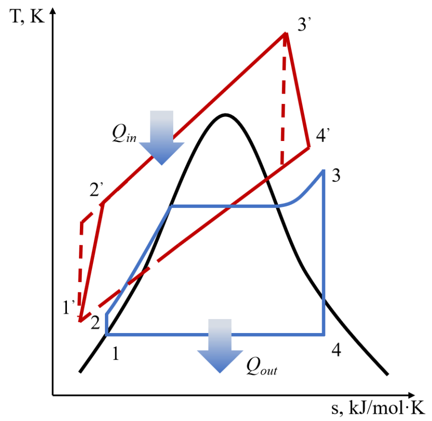

FIGURE 2. Temperature entropy diagram of the combined power cycle.

where $w_{out,t}$ is the output power of the turbine, kJ/kg; $w_{in,c}$ the input power of the compressor, kJ/kg; $w_{in,p}$ the input power of the pump, kJ/kg; $q_{in,f}$ the energy brought by the fuel to the combustion chamber, kJ/kg. The subscripts of *eng* and *PGU* stand for the engine and the PGU part in the module.

B. SECOND LAW OF THERMODYNAMICS AND EXERGY ANALYSIS

The second law efficiency of the combined power cycle is [33], [34]

$$\eta_X = \frac{X_{out}}{X_{in}} \tag{4}$$

where η_X is the exergetic efficiency; X_{in} the total input exergy of the system, kJ/kg; and X_{out} the reversible exergy out of the system, kJ/kg.

The exergy sources of the combined power cycle are fuel and air [35]. Therefore, the input exergy of the combined power cycle can be expressed as

$$X_{in} = X_{in,f} + X_{in,a} \tag{5}$$

where $X_{in,f}$ and $X_{in,a}$ are the fuel and air exergy, kJ/kg.

The fuel exergy can be divided into physical and chemical parts, being $X_{ph,f}$ and $X_{ch,f}$. The physical exergy of combustion fuel gas is [34]

$$X_{ph,f} = C_{p,T}\left[T_f - T_0 - T_0\ln\left(\frac{T_f}{T_0}\right)\right] + RT_0\ln\left(\frac{P}{P_0}\right) \tag{6}$$

with T_f the fuel temperature, K; P the pressure, kPa; $C_{p,T}$ the specific heat capacity of combustion gas, kJ/kg·K; R the ideal gas constant, kJ/kg·K. The subscript 0 denotes the reference states.

The chemical exergy of liquid fuel can be calculated by the Szargut Styryslska formula [33], [34].

$$\begin{aligned} X_{ch,f} = (1.0401 + 0.01728\frac{H}{C} + 0.0432\frac{O}{C} \\ + 0.2196\frac{S}{C}(1 - 2.0628\frac{H}{C}))LHV \end{aligned} \tag{7}$$

where LHV is the low heating value of the fuel [36], kJ/kg; H, C, O, and S are the mass fractions of hydrogen, carbon, oxygen, and sulfur separately.

Supposing that the air enters the waste heat recovery module with the reference temperature, then the air exergy can be equivalent to its kinetic energy as [33]

$$X_{in,a} = \frac{1}{2000}v^2 \tag{8}$$

with v the airspeed, m/s.

The output exergy of the combined cycle equals the net work done by the engine and the PGU [28], [37] because they are reversible power. The expression is

$$X_{out} = w_{net} \tag{9}$$

C. FUEL PENALTY OF THE POWER GENERATION UNIT IN HELICOPTERS

Weight is one of the most vital concerns of the extension of the power converting system to the helicopter [38]. The weight penalty arising from the PGU can be estimated by fuel consumption as it consumes fuel [27]. It contains the fuel consumption for carrying the equipment weight, the fuel consumption for overcoming the additional drag, and the fuel consumption for producing additional power from the engine shaft [39]. The extra weight of the waste heat recovery module is equivalent to the PGU, for the preheated unit is mainly constructed by the original configuration of the helicopter. Assuming that the condenser is air cooling, the fuel penalty of the ORC-based PGU can be described as

$$\Delta M_{T,PGU} = M_{D,PGU} + M_{X,PGU} + M_{N,PGU} \tag{10}$$

with $\Delta M_{T,PGU}$ the total fuel penalty of the PGU, kg; $M_{D,PGU}$ the fuel penalty for carrying the unit, kg; $M_{X,PGU}$ the fuel penalty for overcoming the extra drag, kg; and $M_{N,PGU}$ the fuel penalty for additional shaft power cost, kg.

Expressing each component regarding the specific fuel consumption (SFC) and flight profile, so (10) turns to be

$$\begin{aligned} \Delta M_{T,PGU} = \left(M_{d,PGU} + rP_{x,PGU} + rP_{n,PGU}\right) \\ \times \left[\exp\left(\frac{\mathrm{SFC}\cdot\tau_0}{r}\right) - 1\right] \end{aligned} \tag{11}$$

where $M_{d,PGU}$ is the installation weight of PGU, kg; r the weight-power ratio of the vehicle in cruise, kg/kW; $P_{x,PGU}$ the power loss of PGU due to aerodynamic drag, kW; $P_{n,PGU}$ the output power of engine shaft consumed by PGU, kW; SFC the specific fuel consumption of the engine, kg/kWh, and τ_0 the flight phase duration, h.

The installation weight of PGU has two parts: the fixed weight of the instrument and the working fluid weight. The previous can be a function of the power-to-weight ratio of the PGU. The latter should be more than the maximum cooling requirement among various flight mission phases. Hence, the installation weight of PGU is expressed as

$$M_{d,PGU} = \frac{P_{out,PGU}}{\xi_{PGU}} + \max_{i=1}^{N_i}\{M_{Organic,i}\} \tag{12}$$

with $P_{out,PGU}$ the output power of the PGU, kW; ξ_{PGU} the power-to-weight ratio of the PGU, kW/kg; $M_{Organic,m}$ the required working fluid weight in mission phase i, kg; N_i the total number of flight mission phase.

The aerodynamic drag caused by the cooling air from the inlet is composed of external and momentum drag. Assuming that the external drag and the thrust recovery of the exhaust port are so small that can be ignored. The power loss caused by the aerodynamic drag can be calculated as [39]

$$P_{x,PGU} = \frac{1}{2000} m_{in} \cdot v_{in}^2 \tag{13}$$

where m_{in} is the cooling air mass flow rate, kg/s, and v_{in} the speed of cooling air, m/s.

The PGU is supposed to reduce the power requirement to the main generator which is driven by the engine shaft, resulting in a negative $P_{n,PGU}$. According to (2), it can be expressed as

$$P_{n,PGU} = -(w_{out,t})_{PGU} m_o \tag{14}$$

with m_o the organic mass flow rate in the PGU loop, kg/s.

As the ratio of fuel mass flow to engine power, the SFC is calculated as follows [27]

$$SFC = \frac{m_f}{P_E} \tag{15}$$

with m_f the fuel mass flow rate, kg/h; P_E the engine power, kW.

In addition, for flight phase m with an operation time of $\tau_{o,m}$, a new weight penalty parameter as the fuel penalty rate is introduced as

$$\Delta m_i = \frac{\Delta M_i}{\tau_{o,i}} \tag{16}$$

with ΔM_i the fuel penalty of flight phase i, kg. Therefore, the fuel penalty of the waste heat recovery module concerning the flight profile can be obtained by summing the fuel penalty of every mission phase as

$$\Delta M_{Ni} = \sum_{i=1}^{N_i} (\Delta m_i \tau_{o,i}) \tag{17}$$

IV. RESULT AND DISCUSSION

A. EXERGY ANALYSIS MODEL VERIFICATION

The exergy analysis model is used according to the working condition of Makila 1A1 turboshaft engine illustrated in [33]. The η_X is calculated at 0 m altitude with 0 m/s speed. Reference [33] carries out the exergy analysis of turboshafts by separating the engine into components such as the axial compressor, the centrifugal compressor, the combustor, and the power turbine. The other main calculation parameters are shown in Table 1.

The exergetic efficiencies calculated by the proposed model are shown and compared with [33] in Table 2. With the proposed module, the exergetic efficiency of the turboshaft is 29.34%, which is 6.69% different from the one in [33]. The calculated fuel flow rate and the airflow rate of the core engine are 0.097 kg/s and 4.99 kg/s. In [33], the fuel and air mass flow rates are 0.106 kg/s and 5.5 kg/s separately. Differences of these parameters are all below 10%, which is acceptable in primary efficiency analysis.

TABLE 1. Parameters of makila 1A1 engine.

Items	Symbols	Values
Total temperature of the turbine inlet (K) [33]	$T_{3'}$	1373
Pressure ratio [33]	π_c	10.2
Shaft power (kW) [33]	P_t	1300
Lower heat value of fuel (kJ/kg·K) [36]	LHV	42759.98

TABLE 2. Verification of the exergetic efficiency model with [33].

Items	Reference [33]	This work	Error
Exergetic efficiency (%)	27.5	29.34	6.69%
Fuel flow rate of the engine (kg/s)	0.106	0.097	-8.49%
Air flow rate of the core engine (kg/s)	5.5	4.99	-9.27%

B. THERMAL ANALYSIS OF PGU

The thermal analysis of the ORC-based PGU is conducted regarding different working fluids. R245fa is widely applied in many ORC applications and has a promising future of helicopter onboard use because of being non-flammable. The inlet and outlet temperature of the heat source for heat recovery vapor generator (HRVG) are 700 K and 400 K [10], [25]. Considering the high temperature, working fluids with high critical temperatures like benzene and R365mfc are also investigated [25], [40], [41]. The turbomachinery efficiencies are set according to average values [41]. The working conditions of the ORC-based PGU are shown in Table 3.

The performance of the ORC-based PGU is shown in Table 4. The combination of mass flow rate and the evaporating pressure for each fluid were prior optimized by pinch analysis. Under the mentioned working condition, the m_o of benzene, R365mfc, and R245fa are 0.1843, 0.3455, and 0.4408 kg/s separately. By using benzene, the PGU achieves an output power of 25.399 kW and a total efficiency of 17.73%. The other two working fluids lead to less output power and lower efficiencies. This is consistent with the results of [26]. Because of the high-temperature environment, the HRVG pinch point temperatures are all larger than 20 K, this result is similar to [25].

Since benzene shows a better performance, it will be the working fluid in the rest of this study. However, benzene should be carefully treated on helicopters, because this working fluid is flammable. In case of safety, non-flammable working fluids like R245fa is always a better option. A future study can be carried out to optimize the HRVG design regarding supercritical conditions.

C. PARAMETRIC INVESTIGATION ON WASTE HEAT RECOVERY MODULE PERFORMANCE

Parametric investigation of the fuel penalty $\Delta M_{T,PGU}$ is carried out regarding the preheated temperature of the fuel T_f, the mass flow rate of the ORC m_o, and the power-to-weight ratio of PGU ξ_{PGU}. The ξ_{PGU} is supposed to be sufficient to supply the m_o. A 54.5 min cruise mission phase at 1000 m with a shaft power of 1052.2 kW is understudied. The current

TABLE 3. **Working conditions of ORC-based PGU for using benzene, R365mfc, and R245fa.**

Items	Benzene	R365mfc	R245fa
Critical temperature (K)	562.02	460	427.16
Critical pressure (kPa)	4907.3	3266	3651
Normal boiling point (K)	353.22	313.3	288.29
Global warming potential	20	910	1020
Flammability	flammable	flammable	non-flammable
Evaporating temperature (K)	609	550	506
Evaporating pressure (kPa)	100	300	700
Condensing temperature (K)	350	350	350
Condensing pressure (kPa)	4900	3260	3600
Turbine isentropic efficiency	70%	70%	70%
Pump isentropic efficiency	70%	70%	70%

TABLE 4. **Performance of ORC-based PGU for using benzene, R365mfc, and R245fa.**

Items	Benzene	R365mfc	R245fa
Mass flow rate (kg/s)	0.1843	0.3455	0.4408
Pinch point temperature (K)	48.72	49.5	49.72
Turbine out work (kW)	25.399	15.183	13.358
PGU efficiency	17.73%	10.48%	9.07%

TABLE 5. **Parameters of the waste heat recovery module.**

Items	Symbols	Values
Total temperature of the turbine inlet (K) [43]	$T_{3'}$	1563
Pressure ratio [43], [44]	π_c	17
Compressor efficiency [44]	η_c	0.82
Specific fuel consumption in cruise (kg/kW·h) [43]	SFC	0.2864
Combustion efficiency [44]	η_b	0.98
Free turbine efficiency [44]	η_{ft}	0.91
Lower heat value of fuel (kJ/kg·K) [36]	LHV	42759.98
Preheated fuel temperature (K)	T_f	[290, 360]
Mass flow rate of working fluid (kg/s)	m_o	[0.15, 1.25]
Power-to-weight ratio of the PGU (kW/kg)	ξ_{PGU}	[0.5, 20]
Heat source of HRVG (K) [25]	$T_{4'}$	700
Cooling air flow rate (kg/s)	m_{in}	1

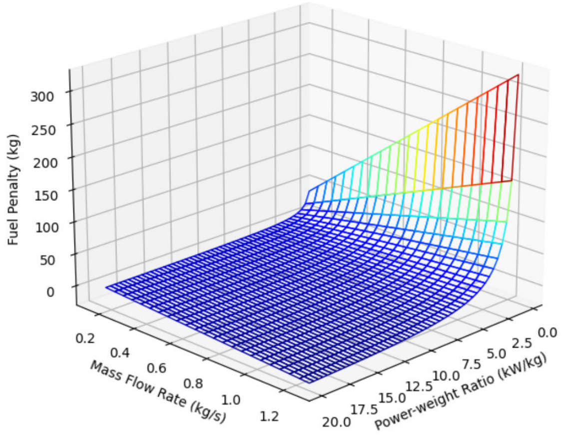

FIGURE 3. **The fuel penalty of the waste heat recovery module regarding ξ_{PGU} and m_o, in a cruise mission with $T_f = 360$K.**

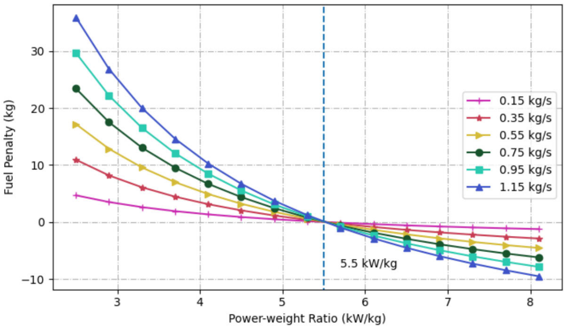

FIGURE 4. **The fuel penalty of the waste heat recovery module regarding m_o, with $T_f = 360$ K, and $2.5 \leq \xi_{PGU} \leq 8.1$ kW/kg.**

parameters of T700 are used and shown in Table 5 [42]–[44]. Researches in [45] and [46] show that the fuel temperature is proportional to the engine thermal efficiency. Therefore, the variables and their ranges are depicted as, T_f is between 290 K and 360 K, ξ_{PGU} is between 0.5 kW/kg and 20 kW/kg, and m_o of benzene is between 0.15 kg/s and 1.25 kg/s. The reference ξ_{PGU} is 3.7 kW/kg, which is achievable value for mini-ORC nowadays [25].

The fuel penalty of the waste heat recovery module $\Delta M_{T,PGU}$ regarding m_o and ξ_{PGU} with a constant fuel temperature of 360 K is shown in Fig. 3. If m_o is fixed while reducing ξ_{PGU} from 5.5 kW/kg to 0.5 kW/kg, the $\Delta M_{T,PGU}$ grows exponentially from 0 to 313 kg. When $\xi_{PGU} > 5.5$ kW/kg, the $\Delta M_{T,PGU}$ of each m_o converges to different negative values.

A zoomed-in area from Fig. 3 is shown in Fig. 4 with $2.5 \leq \xi_{PGU} \leq 8.1$ kW/kg. When $\xi_{PGU} < 5.5$ kW/kg, the $\Delta M_{T,PGU}$ grows while m_o is raising from 0.15 kg/s to 1.25 kg/s. For $\xi_{PGU} = 3.7$ kW/kg, the fuel penalties are 1.91 kg and 15.8 kg when $m_o = 0.15$ kg/s and 1.25 kg/s separately. Hence, the waste heat recovery module with the reference power-to-weight ratio of 3.7 kW/kg must cause additional fuel consumption to helicopters. When $\xi_{PGU} > 5.5$ kW/kg, the $\Delta M_{T,PGU}$ decreases with an increasing m_o. The negative $\Delta M_{T,PGU}$ indicates that although the module installation increases the structural weight, it saves fuel for the helicopter in this situation.

The thermal and exergetic efficiencies, η_Q and η_X regarding m_o and T_f with $\xi_{PGU} = 3.7$ kW/kg are shown in Fig. 5 and Fig. 6. Fig. 5 shows that when $T_f = 290$ K while m_o is increasing from 0.15 kg/s to 1.25 kg/s, the η_Q grows from 34.03% to 36.12%. Fig. 6 shows that the corresponding η_X grows from 26.47% to 28.14%. The 1.1 kg/s more of m_o improves η_Q and η_X by 2.09% and 1.67% separately. But it leads to 13.97 kg extra $\Delta M_{T,PGU}$ as shown in Fig. 7. When $m_o = 0.15$ kg/s while T_f is increasing from 290 K to 360 K, η_Q and η_X grow 0.0022% and 0.0829% separately and the $\Delta M_{T,PGU}$ is barely changed. Hence, T_f should be as high as possible, for it improves the efficiencies but hardly causes the $\Delta M_{T,PGU}$. And m_o, should be small enough to keep the $\Delta M_{T,PGU}$ under an acceptable level.

D. EVALUATION OF THE WASTE HEAT RECOVERY MODULE IN VARIOUS WORKING CONDITIONS

The energy efficiencies are relative to the flight mission phase [47]. Balli *et al.* [34] and Koruyucu [48] chose the maximum power operation mode at the seal level and the take-off phase at various altitudes to perform energy efficiency analyses. In this work, a completed helicopter mission profile with 9 flight mission phases is studied, including a 5 min take-off, 1.3 min climbing, 54.5 min cruise, 2 min decline, 40 min low altitude cruise, 1.1 min high accelerate climbing, 54.4 min

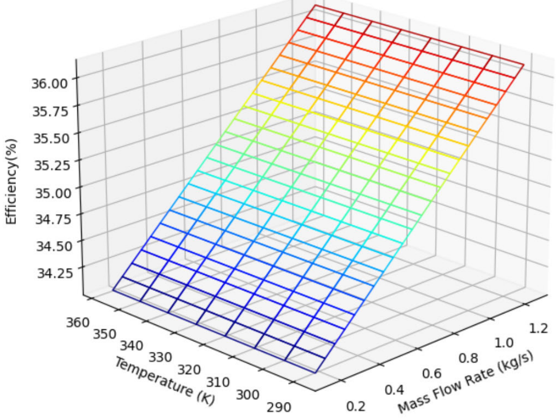

FIGURE 5. The thermal efficiency of the waste heat recovery module regarding T_f and m_o, with $\xi_{PGU} = 3.7$ kW/kg.

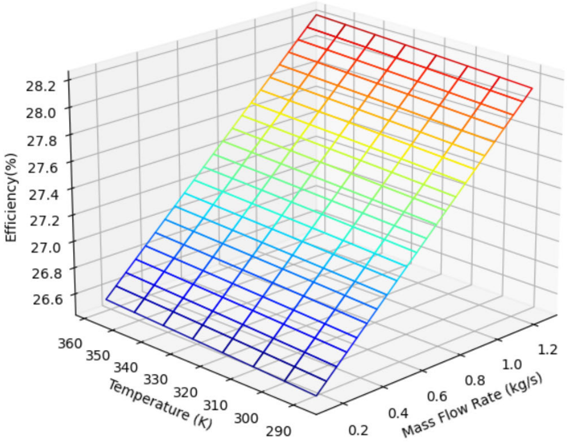

FIGURE 6. The exergetic efficiency of the waste heat recovery module regarding T_f and m_o, with $\xi_{PGU} = 3.7$ kW/kg.

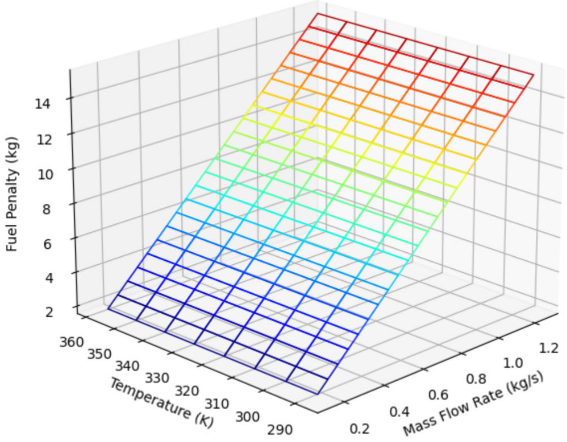

FIGURE 7. The fuel penalty of the heat recovery module regarding T_f and m_o, with $\xi_{PGU} = 3.7$ kW/kg.

cruise, 2.3 min decline, and 3 min landing [49]. The working conditions of each flight phase are shown in Table 6.

According to the previous analysis, parameters of the waste heat recovery module are chosen as $T_f = 360$ K, $m_o = 0.15$ kg/s, and $\xi_{PGU} = 3.7$ kW/kg. The other parameters of the module follows Table 5.

TABLE 6. Various working conditions [49].

No.	Mission phase	Duration (min)	Starting height (m)	Ending altitude (m)	Shaft power requirement (kW)
1	Take-off	5	0	0	763.15
2	Climbing	1.15	0	483	658.85
3	Cruise	42.5	483	483	576.3
4	Decline	1.72	483	60.96	289.6
5	Low altitude cruise	40	60.96	60.96	493.4
6	High accelerate climbing	0.95	60.96	483	596.8
7	Cruise	42.5	483	483	522.4
8	Decline	1.84	483	0	262.3
9	Landing	3	0	0	657.45

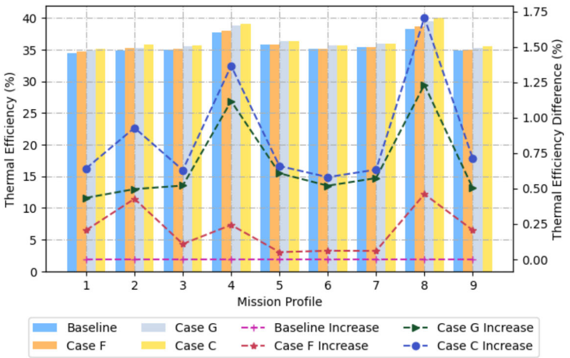

FIGURE 8. The η_Q (the primary axis) and efficiency difference (the secondary axis) of the waste heat recovery module regarding various layouts under a complete flight mission profile.

The T700 engine is the baseline and the core of the proposed module. Three configurations of the module are studied: Case F, only the fuel preheating unit is implemented to the module; Case G, only the PGU is implemented to the module with a fuel temperature of 288.15 K [33]; Case C, both the fuel preheating and the PGU are implemented to the module. In the whole mission profile, Case C leads to $\Delta M_{T,PGU} = 21.32$ kg.

The thermal efficiency result of the whole mission profile is shown in Fig. 8. The η_Q of the reference design in each flight phase are 34.46%, 34.82%, 35.04%, 37.68%, 35.74%, 35.13%, 35.88%, 38.26%, and 34.81%. In flight phases of 5, 6, and 7, the η_Q of Case F are 0.050%, 0.060%, and 0.059% higher than the baseline. Case G increases the η_Q by 0.607%, 0.519%, and 0.573% in the same flight phases. As a combination of cases F and G, Case C has the highest η_Q in every flight phased. In mission phase 8, the η_Q of Case C is 1.706% higher than the baseline and larger than the sum of the improvement made by Case F (0.460%) and Case G (1.232%). The η_Q of Case C in each flight phase are 35.11%, 35.75%, 35.67%, 39.05%, 36.40%, 35.71%, 35.97%, 39.96%, and 35.52%.

The η_X result of the whole mission profile is shown in Fig. 9. The η_X of the reference design in each flight phase are 26.62%, 26.90%, 27.09%, 29.10%, 27.63%, 27.15%, 27.31%, 29.55%, and 26.88%. In flight phases 5, 6, and 7, the η_X of Case F are 0.354%, 0.364%, and 0.374% higher than the baseline, meaning that the exergy destruction is effectively decreased by using the preheated fuel. In the same mission phases, Case G gets higher efficiency improvements

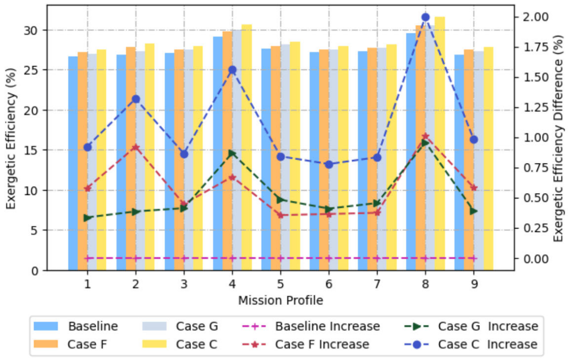

FIGURE 9. **The η_X (the primary axis) and efficiency difference (the secondary axis) of the waste heat recovery module regarding various layouts under a complete flight mission profile.**

as 0.482%, 0.409%, and 0.454%. Case C works the best in phase 8 with an exergetic efficiency improvement of 2%, which is more than the sum of the efficiency difference made by Case F (0.958%) and G (1%). The η_X of Case C in each flight phase are 27.54%, 28.22%, 27.95%, 30.66%, 28.48%, 27.93%, 28.15%, 31.55%, and 27.86%.

Apparently, the proposed PGU module for the tested situation can improve the energy efficiencies but result a positive fuel penalty. It is hard to say if the extra fuel penalty of 21.32 kg is accepted until carrying out a trade-off between the flight performance and the added cost. Before that occurs, the goal of reducing fuel consumption can only be achieved by getting a negative fuel penalty. In this situation, small scale ORC with a power-to-weight ratio higher than 5.5 is requisite though it is difficult to be realized by now.

V. CONCLUSION

In this paper, a waste heat recovery module for helicopters is proposed with the turboshaft engine as the core. The module is a combination of a fuel preheating process and an ORC-based PGU for collecting and reusing the waste heat inside the helicopter and the exhaust gas. Efficiency and weight cost analyses show that benzene makes the PGU be able to produce more output power and thermal efficiency than R365mfc and R245fa. Though PGUs having the existing technologies of expander always cost additional fuel, negative fuel penalties can be achieved with a preheated fuel temperature of 360 K when the PGU power-to-weight ratio is bigger than 5.5 kW/kg. Simulations based on T700 turboshaft engine and a 9-phases flight mission validate that the proposed waste heat recovery module can increase the thermal and exergetic efficiencies by 1.706% and 2% separately. Moreover, the proposed fuel penalty model can reflect the weight cost for the efficiency improvement regarding various working conditions. Possible future work can be carried out by considering other conversion cycles with working fluids which have no limits concerning the maximum temperature of the exhaust gas. Trade-offs between the extra cost brought by the PGU and the flight performance can be another aspect of future study.

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