9th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2017-146**
20-22 September 2017 - METU, Ankara TURKEY

EXERGETIC BENEFITS OF CENTRAL THERMAL SYSTEM FOR SERVING PARKED AIRCRAFTS AT THE GATE

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ABSTRACT

Aircrafts docked to the terminal gate are generally air-conditioned by PCA systems usually mounted under the jetway. In this study, alternative solutions focusing on a central tri-generation plant in the terminal complex serving multiple aircrafts simultaneously with or without ice storage were analyzed and compared to a reference case, namely of which, APU of the docked aircraft itself is used. The alternative with the ice storage option was further investigated by adding ground-source heat pumps. Mainly by using the Rational Exergy Management Model (REMM), all alternatives were compared based on the exergy rationale, energy efficiency, and economy points of view. The impact of ice storage on reducing carbon emissions was further investigated. Results showed that addition of an ice storage system to a central power plant serving multiple jetways reduces the system size, operating cost, and carbon emissions while adding a heat pump further reduces the tri-generation system size but does not improve much the overall performance.

INTRODUCTION

PCA (Pre-conditioned Air) units provide HVAC services to a jetway (aka bridge)-parked aircraft during pre-flight and loading services in modern airports. Two PCA versions are common in Europe: Point-of-use systems mainly in the US and the Far East and jetway mounted systems [Airport Suppliers, 2016; Sikorski, 2010]. Jetway-mounted systems are usually electrically driven, self-contained units that means a suitable air handling unit and pertinent air delivery equipment being mounted under the jetway (see Figure. 1). For remote parking positions, point-of-use systems mounted on a truck are the obvious choice. Both PCA versions may be used in the same terminal. Besides reducing on-site noise and air pollution, this system is claimed to save substantial fuel costs by eliminating the need of using the aircraft's own APU (Auxiliary Power Unit) during docking periods. However, a more complete study presented in this paper based on the primary energy use point of view, shows that this is not necessarily the case to the extent of the claim. Today's "central" PCA, by definition, is not in fact a central system. It is an individual system serving a single aircraft. In broader context, a central system should mean a system that serves multiple aircraft from a main plant with a distribution system for each jetway served. Such a true central system enables to use ground-based, more energy and exergy efficient, even renewable energy resources and systems, like solar tri-generation systems. Today's modern airports and large building complexes already have conventional central tri-generation plants- some running on biogas- and some of them employing ice storage systems [Kilkis, 2014a; Kilkis, 2014b].

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Figure. 1. Jetway-mounted HVAC system: PCA. (Airport Systems, 2016).

A simple extension of the power, heat, and cold services to the jetway by a properly designed and optimized distribution system should be a relatively simple task. A true centralization concept proof, serving 73 jet gates through a piping system of 15 miles at the Sea-Tac Airport in Seattle has won the first place in the 2015 International Tech Awards, sponsored by ASHRAE [Port of Seattle, 2016]. This system is expected to spread out to the world rapidly within the concept of greener terminals while the recently developed new sustainable airport index gives special emphasis to central tri-generation systems with ice storage, if applied [Kılkış and Kılkış, 2016a]. Ice storage systems (ISS) shave off the peak cooling loads and shift them, thus system size is reduced and system is often operated at maximum capacity with optimum efficiency, and may be directly charged by ammonia-absorption chillers coupled to cogeneration systems [Kılkış and Kılkış, 2016b]. ISS is a well proven concept used both in the building sector and in the industry including storage of wind energy in the form of ice where cooling demand is dominant [Kilkis, 2016c]. With the peak load shaving factor *SF*:

$$Q_C = Q_{Cpeak} \cdot (1 - SF) \quad (1)$$

In fact, the APU of an aircraft is a jet fuel driven small example of a potential on-board tri-generation system minus energy storage. Yet, APU uses jet fuel (kerosene mix), pollutes the tarmac, and increases the local noise level. Furthermore, the energy storage on board in order to shave peak heating and cooling loads of the aircraft is not possible due to space and weight restrictions. Even further, the coincident HVAC loads of a single aircraft may not suit the output of the APU. Therefore, it will be prudent to convey the same tri-generation concept to the terminal area. Such a move shall further reduce the installation size by permitting to factor in a certain diversity factor (*DF*) among many aircraft being served:

$$Q_{C\,peak} = \frac{\left(DF \cdot \sum_{i=1}^{p} Q_{Ci}\right)}{p} \quad (2)$$

REMM ANALYSIS

The performance analysis of the reference case, namely the current PCA technology and the centralized alternatives, were primarily analyzed from the exergy rationale point of view by using the Rational Exergy Management Model, REMM [Kılkış, 2012]. REMM considers two distinct cases in terms of the parameter Ψ_R: 1- if the exergy in a process is destroyed before the useful application or 2- after the useful application. Current PCA technology represents the first case. A tri-generation system represents the second case (See Figure 2).

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{\sup}} \quad \text{\{If exergy is destroyed upstream\}} \quad (3\text{-a})$$

$$\psi_R = 1 - \frac{\sum \varepsilon_{des}}{\varepsilon_{\sup}} \quad \text{\{If exergy is destroyed downstream\}} \quad (3\text{-b})$$

$$\varepsilon = \left(1 - \frac{T_{ref}}{T_f}\right) \tag{4}$$

The energy performance indicators, namely, the Primary Energy Savings Ratio as the *PES* metric and the CO_2 emissions metric (prorated to cooling in a tri-generation system) are given below [Kılkış and Kılkış, 2016b]. As an example, for the case of APU that is shown in Figure 2-b, the *PES* value is 43%.

$$PES = 1 - \left[\frac{1}{\left(\frac{CHPH\eta}{\mathrm{Re}\,fH\eta} + \frac{CHPE\eta}{\mathrm{Re}\,fE\eta}\right) \times \left(\frac{2-\psi_{Rref}}{2-\psi_R}\right)}\right] \times 100 \tag{5}$$

$$PES = 1 - \left[\frac{1}{\left(\frac{0{,}52}{0{,}85} + \frac{0{,}37}{0{,}52}\right) \times \left(\frac{2-0{,}2}{2-0{,}648}\right)}\right] \times 100 = 43\%$$

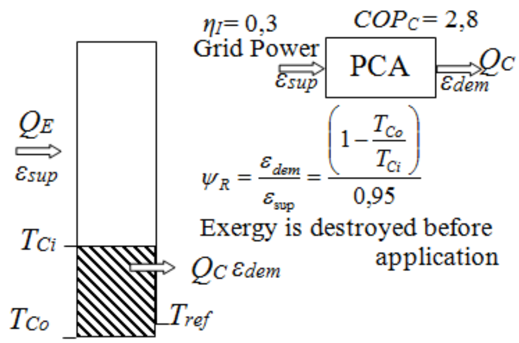
$$CO_2 = Q_f \cdot c_i \tag{6}$$

$$CO_{2_p} = CO_2 \times \frac{1 \times \left(1 - \frac{280}{285}\right)}{Q_E \times 0{,}95 + 1 \times \left(1 - \frac{280}{285}\right)} \tag{7}$$

Figures 2-a and 2-b show the energy and exergy performance differences between current PCA technology and the APU alternative (Base case) from the REMM point of view. Another energy performance factor, namely *PER* is given in Figure 2-a. According to Figure 2-a, Ψ_R of the PCA system is 0.018 W/W, where exergy is destroyed first, while the same value for APU is 0.648 W/W, where the exergy is destroyed later in the process of generating electric power first. In the case of APU, in addition to cooling (or heating) capacity of the PCA system, electric power and heat may be generated, thus the fuel can be utilized more efficiently. However, an on board absorption system and simultaneous utilization of heat on board is impractical. If power generated by APU is equally split between power and on-board A/C system, then Ψ_R reduces from 0.648 W/W to 0.495 W/W. Instead, the APU version of the potential version of the tri-generation concept on board may be transformed to a ground based option in the terminal complex in order to utilize all the power and heat output potential of a tri-generation system.

RESULTS AND DISCUSSION

Table 1 summarizes the results from the analysis. From a technical performance point of view, including cooling attributed hourly CO_2 emissions per docked aircraft, Alternative 2 appears to be an optimum solution, when the results of the cost analysis are factored in. Figure 3 shows the centralized PCA alternatives namely, 1- Central Tri-generation without ISS, 2- Central Tri-generation with ISS, 3- Central Tri-generation with ISS and HP. The PCA system demands electricity (1/2.8 kW_e per 1 kW_c) by consuming it in a chiller with COP_c of 2.8 to produce cold. Alternatives 1, 2, and 3 generate extra power and heat. Operating costs are adjusted with respect to the additional power generated. The lowest additional power generated is for Alternative 3 but this alternative requires the smallest size of the tri-generation plant. The base case is the second least desirable case with respect to CO_2 emissions. However, PCA has higher CO_2 emissions in contrast to the Narita Airport 2015 environment report [NAA, 2015]. The base case (Gas turbine APU) case has the highest installation cost but this cost needs to be prorated to the docking periods over flight time in order to achieve a common-base comparison. Yet operating cost is also the highest on the tarmac.



<u>a- PCA. Only A/C</u>

T_{Ci} = 285 K; T_{Co} = 280 K; T_{ref} = 283 K ;

ε_{sup} = 0,95 kW-h/kW$_e$-h {Electricity}

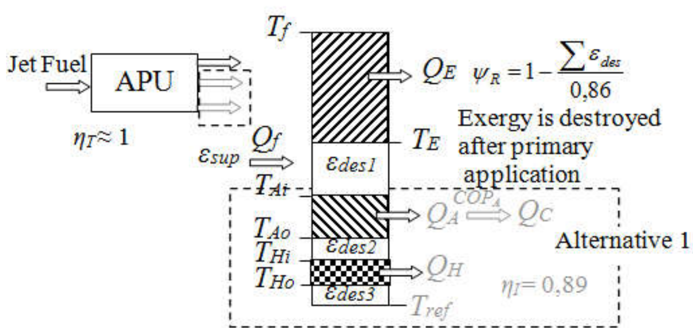
$$\psi_R = \frac{\left(1-\frac{280}{285}\right)}{0{,}95} = 0{,}018$$

$PER = \eta_I \cdot \eta_T \cdot COP_c$ = 0,3 x 2,8 = 0,84

PES = 0 %

$\eta_{II} = Q_c/(Q_E/PER) = \Psi_R \cdot PER$ = 0,015

Figure 2-a. Exergy flow bar and schematics for PCA.



<u>b- APU. Power (potentially heating and cooling)</u>

T_f =2000 K; T_E =500 K; T_{Ai} =450 K; T_{Ao} =383 K; T_{Hi} =363K

T_{Ho} =333 K; COP_A =0,55; $CHPH\eta$ =0,52; $CHPE\eta$ =0,37;

C =1,4; ε_{sup} = (1-283 K/2000 K) = 0,86 kW-h/kW$_f$-h (Fuel)

$$\psi_R = 1 - \frac{\left(1-\frac{450}{500}\right)+\left(1-\frac{363}{383}\right)+\left(1-\frac{283}{333}\right)}{0{,}86} = 0{,}648$$

$PER = \eta_I \cdot \eta_T \approx \eta_I$ = 0,89 {On site}

PES = 43 %

Alternative

$$\eta_{II} = \frac{Q_E + Q_A + Q_H}{Q_f/\eta_I} \approx \psi_R \cdot \eta_I = 0{,}648 \times 0{,}91 = 0{,}59$$

Fig. 2-b. Exergy flow bar and schematics for APU case. Q_c is the unit cooling supply base: 1 kW$_c$-h.

The PCA case has the lowest installation cost and from an owner's point of view, operating cost is moderate. But assume a natural gas plant with 0.35 power generation efficiency for a common base comparison, the extended operating cost is 0.072/0.35 x 0.12 \$/kW-h/0.20

\$/kW-h = 0.123 \$/kW$_c$-h. This cost is the highest. From an operational point of view, Alternatives 2 and 3 can compete with the PCA. Tables 1 and 2 provide the performance and economic comparisons of the alternative cases for one 1 kW$_c$-h per docked aircraft.

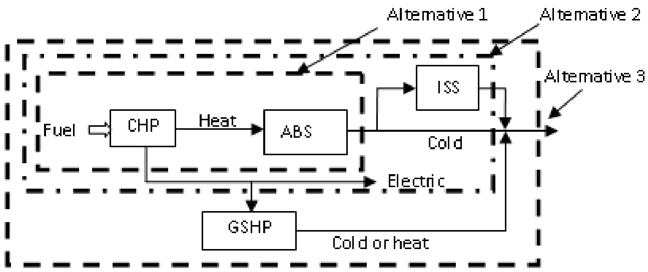


Figure 3. Alternatives 1, 2, 3 for true central PCA alternatives (See Table 1).

Table 1. Performance Comparison of the Cases for one 1 kW$_c$-h per docked aircraft.

CASE		Description	Ψ_R	*PER*	*PES* %	Direct CO_2 Emission kg/kW$_c$-h	Net Power Supplied Per Unit Cooling, kW$_e$ (- means demand)
Current		PCA	0,018	0,84	-	0,480[1]	-0,36
Base		APU (without heat and cold production)	0,495	0,98	-	0,206[1]	0
Alternative	1	Central Tri-generation without ISS[4]	0,648	0,89	43[2]	0,0098[1,3]	+1,3
	2	Central Tri-generation with ISS[6]	0,706[5]	0,93	47,8	0,0095[1,3]	+1,15
	3	Central Tri-generation with ISS and HP[7]	0,51	1,27	53	0,0123[1,3]	+0,43

[1] Cooling attributed, [2] Based on all heat output dedicated to cooling, [3] Exergy prorated between power and cooling, *DF* = 0,8
[4] Double stage ammonia absorption cooling machine, [5] With a bottoming power-generating cycle, T_E = 475 K
[6] Based on 10-hour charging and 8-hour discharging, [7] Ground-source heat pump system

Table 2. Economic Comparison for one 1 kW$_c$-h cooling capacity per docked aircraft.

CASE		Description	Installation Cost \$/kW$_c$	Operating Cost[1] \$/kW$_c$-h	Installed Capacity[2] kW$_e$/kW$_c$
Base		APU (gas Turbine)	1500	0,2	1,02
Current		PCA	500	0,072	0,36[3]
Alternative	1	Central Tri-generation without ISS	910[4]	0,295-0,91x0,20=0,113	0,91
	2	Central Tri-generation with ISS	1100	0,174-0,55x0,20=0,064	0,55
	3	Central Tri-generation with ISS and HP	1800	0,085-0,27x0,20=0,031	0,27

[1] Based on natural gas at a unit cost of 0,12 \$/kW-h and electricity cost of 0,20 \$/kW-h
[2] *SF* = 0,4 (For cases 2 and 3), *DF* = 0,8 (For cases 1, 2, and 3)
[3] Based on a COP_c of 2,8 (outdoors), [4] Unit price for a tri-generation system taken 1000\$/kW$_c$

CONCLUSIONS

Figure 4 shows the cumulative installation and operating costs of the three alternatives. Alternative 1 is the cheapest to install but the most expensive to operate. Alternative 2 - although more expensive to install- compared to Alternative 1, it breaks even with Alternative 1 after about 4000 hours of operation. In the same token, Alternative 3 breaks even with Alternative 1 in about 11500 hours and with Alternative 2 after 23000 hours. Results show that ISS makes the performance better and pays back in a short period of time. Adding a ground-source heat pump makes the system moderately better. Alternative 2 can also be mounted on a tug so that the true centralized PAC system may be reduced to a mobile system until the aircraft is tugged up to the take-off runway. Such a solution is expected to largely decrease the air pollution, CO_2 emissions, jet fuel consumption, and thus ground operation of the aircraft.

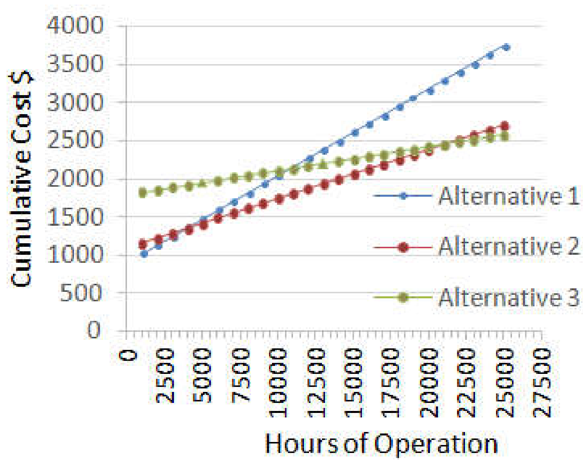


Figure 4. Cumulative cost of alternatives.

NOMENCLATURE

c_i	Unit CO_2 emission, $kgCO_2/kW$-h
CO_2	Carbon Dioxide Emissions, kg/kW_c-h
CO_{2p}	Cooling Load Prorated CO_2 Emission,
DF	Diversity Factor
p	Number of air planes served
PER	Primary Energy Ratio
PES	Primary Energy Savings Ratio
Q_{cpeak}	The peak cooling load, kW_c or kW_c-h
Q_C	Shaved-off cooling load, kW_c or kW_c-h
Q_E	Power output, kW
Q_H	Heat output, kW
Q_f	Input fuel power, kW
SF	Peak Load Shaving Factor
T	Temperature, K

Greek Symbols

Ψ_R	Rational Exergy Management Efficiency
ε	Unit Exergy, kW/kW or kW-h/kW-h
ε_{dem}	Unit Demand Exergy, kW/kW or kW-h/kW-h
ε_{des}	Unit Destroyed Exergy, kW/kW or kW-h/kW-h
ε_{sup}	Unit Supply Exergy, kW/kW or kW-h/kW-h
η	First-Law Efficiency

Subscripts

A	Absorption
c	Cooling
H	Heat
I	First-law
II	Second-law
ref	Reference
T	Transmission and transformation of power
i	In
o	Out

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