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Application of Exergy Analysis for the Aircraft Environmental Control System

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Abstract **Exergy Analysis has found application in many applications of component and system optimization. It combines the use of the first law of thermodynamics that allows to take account of all types of energies to satisfy the conservation of the total amount of it in any process with the second law that gives the directionality and the quality of the energy and its degradation. The application of exergy methods may lead to more effective methods for compact heat exchangers at the component level and at system level for a lower life cycle cost. Aircraft Environmental Control System (ECS) being the primary consumer of the secondary power developed by the engine, is yet to utilize the full potential of the exergy analysis for the optimization of its components and the configurations. This paper surveys the work done in application of the exergy analysis for the design and development of the Aircraft ECS till date.**

Keywords — Air Cycle Machine, Aircraft Environmental Control System, Compact Heat Exchanger, Exergy Analysis, Optimization, Two Phase Heat Transfer

I. INTRODUCTION

The journey of Exergy Analysis (EA) starting from the introduction of the term Exergy in 1953 by Zoran Rant to 2004 was covered in detail by E. Sciubba and G. Wall [1] with more than 2600 references [2]. EA combines the use of the first law of thermodynamics [3] that allows to take account of all types of energies to satisfy the conservation of the total amount of it in any process with the second law that gives the directionality and the quality of the energy and its degradation. It was predicted [3] that the application of exergy methods may lead to more effective methods for areas including fin selection for compact heat exchangers (CHE). Not much of published data was available at the time of publishing of that paper on EA of CHE, which are the primary components in many heat transfer applications including the Aircraft Environmental Control System (ECS), the primary function of which is air-conditioning.

This paper looks at the work done in application of the EA to the Aircraft ECS, Air-conditioning Systems and Compact Heat Exchangers. Apart from the above, an attempt is made to carry out a review of the published work in the area of application of the EA for the design and development of Aircraft ECS till date.

II. AIRCRAFT ENVIRONMENTAL CONTROL SYSTEM

Aircraft is a system of integration of complex systems to achieve the intended purpose of the aircraft in the most efficient manner. The drivers for the advances in the development of these systems apart from the functional requirements are the environmental and other safety regulations and the availability of new technologies [4]. EA provides the common currency to optimize these diverse complex systems locally at component level, system level and globally at aircraft level. The first application of EA for the engine of an aircraft was in 1956 by Glansdorff [1]. It is not surprising that the EA was extensively used so far for the development of propulsion system of the aircraft, as it is the main source of energy on the aircraft and any aircraft operation depends hugely on the performance of its propulsion system. There were applications of EA in the other aspects of aircraft development like aerodynamics, wing analysis and ECS. But the penetration was not as pronounced as had been for the propulsion system.

The cooling requirements keep increasing with the ever-increasing avionics heat loads in each new aircraft development as well as the ongoing update programs on older aircraft. ECS in meeting these requirements becomes the major consumer of the secondary power developed by the engine and thus the dominant user of the exergy [5]. Hence, it is undoubtedly the system that should make use of the optimization provided by EA.

There are different configurations possible while designing an ECS for an aircraft based on air cycle systems, vapor cycle systems and hybrid systems. Different types of components like compact heat exchangers, valves, air cycle machines, compressors, jet pumps, water extractors, pressure regulators, heaters, venturis etc. make up these systems [6]. In these components the compressible moist air flow along with the phase change heat transfer is required to be taken care of. Like in all aircraft applications of EA, the changing environmental conditions like pressure, temperature and humidity are to be accounted for as the exergy in the system is measured from the dead state i.e. the surrounding environmental conditions.

In a special section of exergy in the Journal of Aircraft D.J. Moorhouse gives an introduction to exergy [7] and explains how the exergy and thermoeconomics which were applied in the design of ground power stations were extended as a methodology for the design of the complete integrated system of systems of an aircraft in [8].

III. REVIEW PAPERS

There are many review papers available on EA which are either application specific or general in nature. Some of

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the review papers are useful from the sub-system point of view (e.g. vapor cycle system or refrigeration system) while others are from component point of view (e.g. heat exchanger).

D.J. Moorhouse along with D.B. Paul and D.M. Pratt [9] discussed the Multi-Disciplinary Optimization (MDO) methodologies employed in design of an aircraft from the view point of a system of systems. The use of energy-based methods was presented, and it was concluded that these methods can be used during conceptual stage in a revolutionary design. An evolutionary design using traditional methods can be audited by these energy-based methods at any stage of the design process to identify the use and wastage of energy.

J.U. Ahamed, R. Saidur and H.H. Masjuki paper [10] reviewed the possibilities of exergy analysis in vapor compression refrigeration (VCR) applications. The dependence of exergy on evaporating temperature, condensing temperature, sub-cooling, compressor pressure and the environmental temperature were highlighted. Exergy efficiency variation with different refrigerants having low ODP and GWP was analyzed. It was also shown that the compressor plays a major part in exergy losses of the VCR system. Pradhumn Tiwari and Prakash Pandey [11] also presented a review of exergy analysis of VCR cycle with different refrigerants to study the components of the system separately.

In a 2012 paper [12] M. Mohanraj, S. Jayaraj and C. Muraleedharan reviewed the application of artificial neural networks (ANN) methods for the energy and exergy analysis of refrigeration, air-conditioning and heat pump systems. In a follow-up paper of 2015 [13] they reviewed the application of ANN methods for the thermal analysis of heat exchangers. K. Manjunath and S.C. Kaushik [14] presented a review of second law of thermodynamic analysis of heat exchangers. Various performance parameters such as entropy generation, exergy analysis, production and manufacturing irreversibility and two-phase fluid loss were considered in their review.

Thermodynamic irreversibility of heat and mass transfer components and systems and the design of these devices based on entropy generation minimization was reviewed by Adrian Bejan in his 1987 article [15]. The review focused on the fundamental mechanisms responsible for the generation of entropy in heat and fluid flow and on the design trade-off of balancing the heat transfer irreversibility against the fluid flow irreversibility. Applications were selected from the fields of heat exchanger design, thermal energy storage, and mass exchanger design. The Constructal law that accounts for contradictory end-design statements such as minimum entropy production and maximum entropy production, and minimum flow resistance and maximum flow resistance was reviewed by A. Bejan [16] detailing how the optimization fits in the design evolution.

Brayton cycle is employed in aircraft propulsion systems and reverse Brayton cycle is employed in aircraft ECS air cycle systems. W.G. Le Roux, T. Bello-Ochende and J.P. Meyer [17] reviewed the optimization studies of a solar thermal Brayton cycle. The method of total EGM was highlighted as it allows heat transfer and fluid flow terms to be available for optimization in a single equation for simultaneous optimization of geometries of various components of the system.

David Hayes, Mudassir Lone, James F Whidbone and Etienne Coetzee reviewed the methods of EGM and EA for aerospace applications [18]. They concluded that the EA is an excellent tool for optimizing individual sub-systems. However, they opined that the true potential of the method could only be harnessed by applying it for the top-level system of systems optimization. It could be done at any stage of the design over the entire mission profile to highlight the locations of exergy destruction. Along with José Camberos the authors have reviewed the use of exergy analysis in Aerospace [19]. This review justifies how thermodynamic exergy analysis has the potential to facilitate a breakthrough in the optimization of aerospace vehicles based on a system of energy systems, through studying the exergy-based multidisciplinary design of future flight vehicles.

Hiren K. Bapodara and Jaspal B. Dabhi [20] reviewed the EA of packaged air conditioning system to improve its Coefficient of Performance (CoP). They reported that less work is done on usage of EA of packaged air-conditioning process.

Daniel Bender [21] giving a survey of the published work focused on the methods of exergy and energy analysis applied to ECS, splitting the exergy destruction in each component into different parts. This method enables a realistic assessment of the potential for improving the thermodynamic efficiency of each component.

And finally in a chapter in the book edited by Jovan Mitrovic, titled “Heat Exchangers-Basics Design Applications” [22], M.M. Awad and Y.S. Muzychka gave a review of the EGM method for heat exchangers.

IV. EA APPLICABLE TO THE AIRCRAFT ECS

Application of EA at component level, sub-system level and system level is given in the following sub-sections:

A. Heat Exchangers:

The compact heat exchangers are indispensable in any aircraft ECS, both in air cycle and vapor cycle systems. It is also the component that contributes to the maximum destruction of the exergy in the system. Hence, optimization of the same is tried by many authors for different configurations and flight conditions.

Thermodynamic optimization of finned crossflow heat exchangers for aircraft environmental control system [23] and Integrative thermodynamic optimization of the environmental control system of an aircraft [24] were presented by J.V.C. Vargas and A. Bejan. Along with D.L. Siems they authored the optimization of the crossflow heat exchanger of an aircraft [25]. In these papers the authors have shown optimization at component level and at an integrated system level. The thermodynamic (Constructal) optimization of the flow geometry applicable to any system that runs based on a limited amount of fuel (exergy) installed onboard was presented. EGM in a crossflow heat exchanger used in aircraft ECS with ram air on the cold side

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was optimized for its geometric features by A. Alebrahim along with A. Bejan [26]. They further studied [27] several architectural features deduced from the same principle: the relative position of the two heat exchangers, their relative sizes, and all the geometric aspect ratios of the two heat exchanger cores. Thermodynamic optimization of geometric structure in the counterflow heat exchanger for an environmental control system was reported by T. Shiba and A. Bejan [28]. Experimental analysis of heat exchangers from exergy point of view can be found in [29]–[32]. Second law based performance evaluation and optimization of the heat exchangers was elaborated in [33]–[37]. Multi objective optimization of heat exchanger design was recommended by J. Guo, L. Cheng and M. Xu [38]–[40]. Application of EA for performance evaluation and optimal configuration of a condenser was dealt in [41], [42].

A design procedure for offset strip fin heat exchangers was proposed on the basis of minimum entropy production criteria by C. Shenone [43]. Entropy generation extrema and their relationship with heat exchanger effectiveness was presented by R.K. Shah and T. Skiepko [44] showing the Number of Transfer Unit (NTU) behavior for complex flow arrangements. The EGM based approach for a plate and fin heat exchanger of a heat recovery system was given by Jaingfeng Guo [40]. This type of heat exchangers are extensively used in aircraft ECS.

Due to change in flight conditions and operation at different altitudes, the environmental conditions vary vastly in case of operation of an aircraft and its systems. Finding the exergy balance was illustrated for many applications including an aircraft heat exchanger by Yalcin A. Göğüş, Ü. Çamdali, and M. Ş. Kavsaoğlu in [45].

B. Air Cycle Machines:

In an air cycle system of an ECS, the heart of the system is the air cycle machine. Different types of air cycle configurations are in use like the boot-strap type, turbo fan type, three-wheel and four-wheel configurations etc. While thermodynamic study of these machines is available in SAE standards like AIR1168, there are papers detailing the thermodynamic performance of these machines [46]. The EA of an aircraft air cycle machine at cruise altitude was done by Ayaz Süleyman Kağan, A. ÖNDER, T. H. Karakoc, and E. A. Bilecik [47]. A dynamic air cycle machine model was developed by M. Bracey, S. R. Nuzum, R. A. Roberts, M. Wolff, and J. Zumberge [48] to carry out the transient EA.

C. Sub-system Vapor Cycle System (VCS):

There are EA studies done on ordinary VCS for ground applications. Jing-Nang Lee, C. Chen, and C. Ting [49] studied the influence of varying ambient temperature on the devices exergy of an air-conditioning system. The exergy efficiencies of simple, boot strap and vapor cycle systems was calculated by Seda Tuzemen, O. Altuntas, M. Z. Sogut, and T. H. Karakoc [50] while investigating the humidity effect in aircraft ECS.

D. System level EA studies of ECS:

R.S. Figliola and R. Tipton [51] using the EA and traditional energy method tried to optimize the weight of an aircraft ECS. Even though they found that the comparison is not direct, they agreed that the EA provides information to optimize the component and the system during design phase. They have opined that further progress is necessary to establish the advantage of using EA in the design of integrated systems. This conference proceeding was again published in the Journal of Aircraft in 2003[52], which was referred by Sciubba and Wall [1]. Based on an earlier work [53] and the later works as mentioned above, Richard S. Figliola, Robert Tipton and Haipeng Li had written in chapter 4 of [54] the use of EA in conception and assessment of aircraft systems. Salient points of the chapter are:

- ECS of an advanced aircraft encompassing seven integrated sub-systems was considered, while the details of ACS, Oil & Hydraulic details are excluded.
- VCS with R-12 & R-114 compared
- Cruise conditions are used for analysis
- Each component of the system is evaluated in terms of its entropy generation
- Pareto optimal design set generated through the multiple objectives to minimize entropy generation and system GTW

Under the guidance of M.R. von Spakovsky, the optimization of a propulsion system of an aircraft that is coupled to an ECS was studied by J.R. Munoz [55]–[57], the EA based optimization of a fighter aircraft systems including ECS was studied by V. Periannan. The thesis of Periannan [58] considered a boot strap air cycle configuration ECS to bring out the exergy destruction in the system components for four objective functions. In a paper that followed [59] the authors suggested that EA may be more beneficial in revolutionary system designs.

EA was used to compare the conventional air bleeding with the electric power off-take for aircraft ECS by H. Jiang, S. Dong, and H. Zhang [60] for a commercial aircraft. While they concluded that the air bleeding is more efficient, Yitao Liu, J. Deng, C. Liu, and S. Li [61] indicated greater efficiency in terms of fuel consumption in the electric architecture. R. Gandolfi, L. F. Pellegrini, G. A. Lima da Silva, and S. de Oliveira Junior carried out the trade-off studies of ECS using EA as a design comparison tool [62], [63] and applied EA to a complete flight envelope of a commercial aircraft [64]. Simulating the ram air inlet adjustment door opening, EA was performed by Yang Juan [65] on the ECS of a civil aircraft.

Thermoeconomic analysis and optimization of aircraft environmental control system was detailed by T.J. Leo and I. Perez-Grande in [66] & [67]. On similar lines the optimization of the heat exchanger for a simple ECS system was done by Li Hong-bo, D. Xin-min, G. Jun, C. Yong, and L. Ting-ting [68].

Daniel Bender's thesis [69] is about applying the EA to the Model based design of aircraft ECS. Salient points of the analysis were:

- Three Wheel Bootstrap cycle

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- Restricted to components that contain the appropriate equations
- Model based design based on Modelica modelling language and libraries of Dymola
- For Take-off, Cruise, Landing and Taxi conditions Exergy destruction and η were compared

The results showed that the turbo components (Fan, Compressor & Turbine) show best exergy efficiencies and lowest variations. The Main Heat Exchanger (MHX), Condenser & Reheater should be addressed first for optimization as they are the biggest exergy destroyers in the system. Optimizing the operation strategy for the TCV and Injector could improve their exergy efficiency.

Kirk A. Clem, G. J. Nelson, B. L. Mesmer, M. D. Watson, and J. L. Perry [70] carried out the EA of ECS and LSS of the International Space Station by developing the exergy balance equations to allow exergy efficiency calculations and system optimization.

V. DISCUSSION

ECS of an aircraft is a complex system involving compressible flow and phase change heat transfer, catering to wide variety of requirements ranging from human comfort to avionics cooling. It integrates with many aircraft systems starting from the engine to the cabin. The number of components and the different types of configurations that they make up give ample scope for optimization. The conventional development depended on rules of thumb and trade of analysis relying on designers' experience. Many authors have recommended the use of EA for the integrated development of these systems to meet their varied requirements in an optimal way. The thermodynamic irreversibilities at component, sub-system and system levels can be evaluated for all flight conditions and missions to evaluate the exergy efficiencies, exergy destroyed rate and the cost there off. Multi objective optimization can be carried out to study various configurations to select the optimal solution.

Out of the various components of the ECS, the compact heat exchangers are the most prominent. The medium of heat transfer could be air (moist air), refrigerant (mixtures), phase change materials, hydraulic oil or fuel. The literature is available in abundance giving the theory and the models to carry out the EA of heat exchanger. The entropy generated due to the pressure loss and the heat transfer on the charge and coolant sides can be calculated based on the overall dimensions and the fin details. In future the effect of the Nanofluids on the exergy efficiencies of these heat transfer devices would be studied.

The heart of an air cycle ECS is the cold air unit. Different configurations in the form of simple, boot strap, 3 wheel and 4 wheels are available. However, the basic units are the compressor, turbine and fan. In some configurations jet pump is also used, but from an EA point of view that would be the least preferred because of its poor thermal efficiency. The models for the basic units are well established and can be extended for the EA of these air cycle machines.

The pressure drops and the heat and mass transfer of all other components like valves, water separator, heater etc. can be added while the different configurations are studied and evaluated. Since the contribution due to most of these components in terms of exergy destruction is negligible compared to the heat exchangers and the air cycle machines many a time they are not included in the analysis.

Thermoeconomic analysis and optimization of a simple aircraft environmental control system was detailed by T.J. Leo and I. Perez-Grande in [66] & [67]. The study was extended for configuration studies involving the complexities from practical applications [71] & [72].

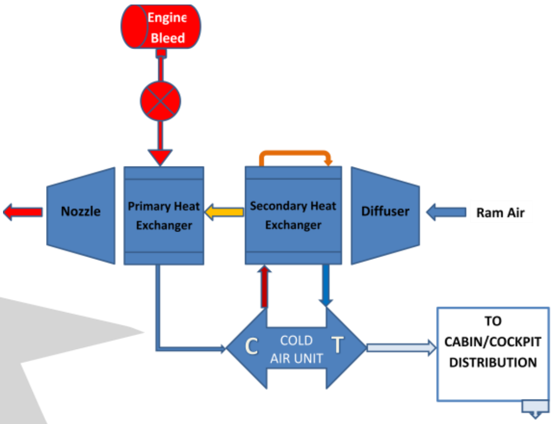

FIGURE 1 SIMPLE SYSTEM STUDIED IN [66] & [67]

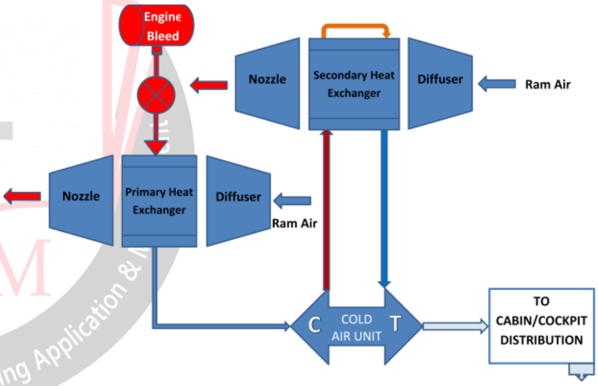

FIGURE 2 PRACTICAL SYSTEM STUDIED IN [71]

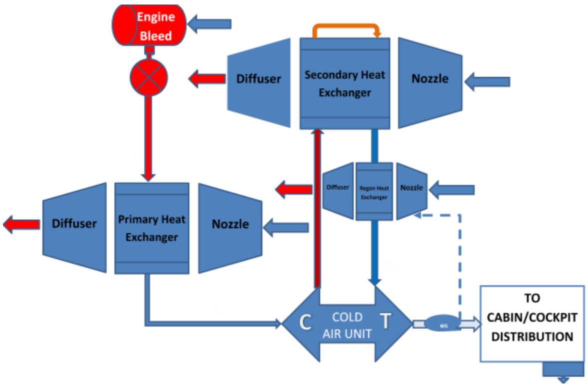

FIGURE 3 EXTENDED CONFIGURATION STUDIED IN [72]

Mathematical models for each of these configurations have about 200 variables with as many equations including assignment of values. This number would keep increasing as we add more components in to the architecture depending on the performance and safety requirements. For the chosen flight conditions, bleed conditions can be evaluated from the basics incorporating the engine

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compressor and ram air efficiencies and checked with the engine bleed conditions that were obtained from the engine deck. After evaluation of the variables, the unknown variables with a smaller number of equations are to be analyzed.

The objective functions are to be framed, for which the parametric study and sensitivity analysis can be done. For example, the Entropy generation number (Ns) and the total volume of three heat exchangers, as given below, could be the objective functions.

$$Ns = ln\frac{T_5}{T_a} - \frac{\gamma-1}{\gamma}ln\frac{p_5}{p_a} + \lambda_p ln\frac{T_9}{T_a} - \lambda_p\frac{\gamma-1}{\gamma}ln\frac{p_9}{p_a} + \lambda_s ln\frac{T_{13}}{T_a} - \lambda_s\frac{\gamma-1}{\gamma}ln\frac{p_{13}}{p_a} + \lambda_r ln\frac{T_{17}}{T_a} - \lambda_r\frac{\gamma-1}{\gamma}ln\frac{p_{17}}{p_a}$$

$$V_T = \left(L_{x1}L_{y1}L_{z1}\right) + \left(L_{x2}L_{y2}L_{z2}\right) + \left(L_{x3}L_{y3}L_{z3}\right)$$

The effect of introduction of water separator and reuse of the water through spray at the inlet of SHE shows that, there is a reduction of about 2.5% in the entropy number. When a small RHE is introduced parallel to the SHE with water sprayed at its inlet, it results in a reduction of about 20% in the total volume of the heat exchangers. Thereby, the total system weight would reduce to similar extent meeting the system performance requirements. Typical parametric plots generated in these configurations are given in Figure 4.

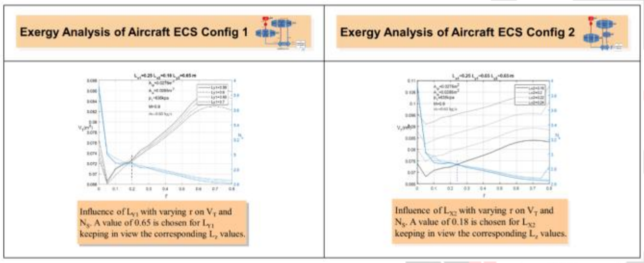

Figure 4 Parametric Plots

Sensitivity analysis can also be carried out to check the effect of various parameters on the objective functions. An example plot is shown in Figure 5.

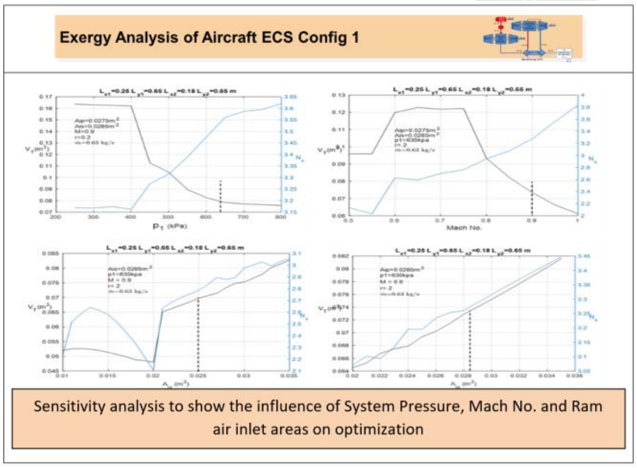

Figure 5 Sensitivity Plots

As can be seen from the above EA can effectively be used at the system architecture level for the configuration studies as well as optimization of the components of the system. Parametric studies and sensitivity analysis to study the effect of various parameters including the geometric values of the components can be carried out leading to the MDO of the system and the components. Further studies to evaluate the effect of moisture at other flight conditions, and more configuration studies to include the high-pressure water separation can be taken up. The MDO with EA can be extended to VCS configurations of ECS to optimize the components involving refrigerant phase change on the same lines of water injection at RHE inlet as was done in [72].

VI. CONCLUSION

Many authors have put forward the utility of the EA in providing the common currency between various integrated complex systems of an aircraft in developing optimised solutions. Even though EA is extensively used for optimisation of the aircraft engine, it is less used in the development of other aircraft systems. ECS being the main consumer of the secondary power generated by the engine to meet various performance requirements of the aircraft, is definitely the candidate for making use of the EA for its optimization providing the sufficient conditions for system feasibility, directionality and performance.

Literature is available on the application of EA at component, sub-system and system level EA. The models and the theory of EA of the main components of the ECS are presented in many papers. The models developed therein could be extended to the newer developments like new fin configurations at CHE level and to newer configurations at system level to carryout the MDO of the aircraft ECS.

The configuration studies of the ECS that consist of so many components can be performed for new developments as well as the system updates. An example of the EA applied for configuration studies of an aircraft ECS along with the optimization of major components is given to high light the usefulness of EA wherein practical systems with the inclusion of phase change due to moist air was studied.

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