

# Design of a Heating Chamber for Air Turbines: A Method of Optimizing Its Efficiency

## ABSTRACT

Increasing comfort, conveniences and reducing carbon-emission into the atmosphere have been the research focus of many researchers in various field of science. SDGs have one of her goals to be zero carbon emission. In order to achieve this goal, carbon combustion must be eliminated in heat engines. This can be done by developing thermodynamics processes that would not use organic fuel as their working fluid. Following this knowledge, researchers found the use of abundant natural resources such as solar, water, wind, and air known as renewable energies also hydrogen and synergy gases as replacement to carbon combustion. However, due to high first cost of these renewable energies and their low mechanical and overall efficiencies, they failed in some applications.

In order to increase the mechanical efficiency of air turbines, the internal energy of air must be increase. Therefore, this research paper developed a heating chamber for air turbines working on an isobaric expansion process in order to raise the temperature of air to the required temperature for it to roll turbine rotor blades efficiently. The heating compartment is intended to follow the adiabatic compression process of an air compressor section of the air turbine layout. The heating compartment has it heat source to be an electric heater and the compressed air as it heat sink. The thermal and economic efficiency of the heating chamber as a section of air turbine was determine using Levelized Cost Method of Moran.

The heating compartment raised the compressed air temperature to the required hot temperature at a constant pressure.

Key word: Air Turbines, Heating Chamber, Mechanical Engineering, "Turbine power

## Nomenclature

$d_c$  diameter of the circular pipe

$n_c$  number of cycles.

$P_c$  circumference of the circular section

$L$  length of pipe

$K_C$  conductive heat transfer coefficient of copper  $P$  electric power supply

$d_t$  tube diameter

$Q'$  quantity of heat

$A$  area of the circular section

$r$  radius of the circular section

$T$  temperature

$h_{FA}$  convective heat transfer coefficient of forced air

$ds$  entropy

$C_p$  specific capicity of air at pressure

$h$  enthalpy

$\dot{C}$  cost rate

PEC Purchased equipment cost of air heater  $SV$  salvage value

PWF Present worth factor

CRF capital recovery factor

i interest rate

n time period

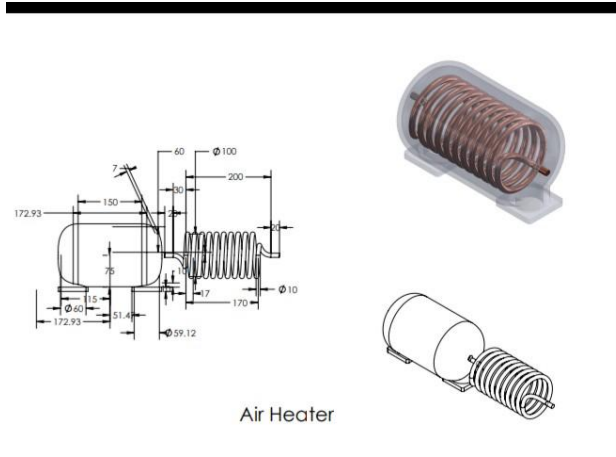
## 1.0 Introduction

Energy is considered a player in the generation of wealth and also a critical component in economic development of a nation. [1] As important energy is, also its generation method has to be considered in order to minimize its cost of generation and other negative effects associated with its generation such as environmental factor and safety. As an attempt to develop the best method of energy generation, Renewal Energy is accepted as a key source for the future [1] and in order to make the future present; a lot have done in renewal energy research. Rohatgi et al. (2020) defines renewable energy as energy derived from natural resources that replenish themselves in less than a human lifetime without depleting the planet's resources.[2] Although renewable energies are considered to be the future of energy, they all faced a similar problem of moderately low efficiency. [3]

Air which is a renewable natural resources and the cheapest fuel is less considered as renewable energy source because of its low internal energy at its free mode. Many methods have been developed to optimize the efficiency of air turbines. Falcons et al. (2016) developed power optimization for air turbine.[4] Although, air turbine has been used in various applications such as wave energy converter [4-15] but its low efficiency is still a concern. In wave energy conversion using the principle of oscillating water column a self rectifying air turbine is used in order to eliminate rectifying valve.[16] This approach increases the cost efficiency of air turbine in the application of wave energy conversion. Air turbine in its natural state needs mechanism to raise its energy in order to give efficient rotating power. After of wave energy, air compressor is also commonly used to increase air energy for air turbine applications. [17-21] Department of Energy is seeking for methods of raising compressed air temperature.[17] With this mission, we designed a compressed air turbine with a heating compartment to raise the temperature of compressed air at constant pressure.

Following the model of a gas turbine, the heating compartment section precedes the air compressor and follows by the turning section like the combustion chamber is of a gas turbine. The thermodynamic cycle of the compressed air turbine is close to gas turbine cycle and Bryton cycle with a slight difference of isobaric expansion. This paper reported the efficiency optimization contribution and cost rate contribution of heating compartment to an air turbine. The heating compartment is synonymous to an air heater which is used in various applications to transfer heat energy. In this case, heating air is for the purpose of raising its initial energy efficiency.

## 2.0 Materials and Methods



**Fig 1: Air Heater**

Solidwork CAD software was used to design the heating compartment section and it made of the outer chamber, liner, air liner and the heater pipe. The outer chamber is made of low carbon steel, the liner is made of brass and the heater pipe is made of copper. The heater pipe is design to be powered by 1000W of Electrical true power.

Parameters  $d_c=100\text{mm}$ ,  $n_c=10$ ,  $d_t=10\text{mm}$

The total length of tube of the circular section of pipe ( $L$ ) =  $n_c P_c = \pi n_c \phi_c = 1000\pi\text{mm} = \pi\text{m}$

10mm was chosen for the heater pipe diameter so that the design air gap will not exceed 3cm in order to optimize the heat transfer efficiency [22] After a logical analysis of pervious report of the geometry of heat exchanger of an air heater and their effectiveness [23-36] a circular heater was used in the design will a sectional length of 170mm and a diameter of 100mm. Copper was selected as the pipe material because of its high thermal conductivity, its high electrical conductivity, it is cheap, it is available and it ability withstand the working temperature range of 150-200°C of the heating compartment. [37] brass is used for the liner in order to provide enough allowance for thermal expansion and to provide a closed system for the heating compartment. In order for the heating compartment to have adequate rigidity and to withstand vibration and other external forces, low carbon steel is selected for the outer casing. [38] The design is made for the sudden temperature change of the system.

## 3.0 Heat Transfer

1000w of electrical power will be supply to the copper tube conductor to raise it temperature from 0°C and the heat generated will be transferred to the air and to the outer casing.

$$Q' = -K_c \frac{dT}{dx} \quad Q' = \frac{P}{A} \quad P = 1000\text{w} \quad A = \pi r(r + L) \quad r = \frac{d_t}{2} \quad r = 0.005\text{m} \quad L = \pi\text{m} \quad dT = T_0 - T_1$$

$$dx = L \quad T_0 = 0^\circ C \quad T_1 = ? \quad T_1 = 158.51^\circ C$$

The temperature of the outer casing is determine by the heat of convection from the heater pipe to the casing through forced air

$$Q' = h_{FA}(T_1 - T_{out}) \rightarrow \text{Newton law's of cooling with forced air as it medium. } h_{FA} = 500 \text{ } w m^{-2} k^{-1} \quad Q' = 17123.29 \text{ } w m^{-2} \quad T_1 = 158.51^\circ C \quad T_{out} = ? \quad T_{out} = 124.25^\circ C$$

#### 4.0 Thermodynamics

It is the isotopic expansion process with a slight change in volume

$$\frac{T}{Cp(T)} = \frac{\partial T}{\partial s} \Big|_P \quad [39] \quad Tds = Cp(T)dT \quad ds = Cp dT \quad ds = Cp(T_1 - T_0) \quad T_0 = 0K \quad T_1 = 158.32^\circ C = 431.52K \quad ds = Cp(T_1 - T_0) \quad ds = 1.005kg = 431.52 \quad ds = 433.6776 \text{ } kJ/Kg \rightarrow \text{entropy}$$

Therefore there's an increase on energy of the working fluid (compressed air) by 433.68kJ for every kilogram of air

#### 5.0 Energy Costing Analysis

The cost contribution of a heating compartment to an air turbine per year is determined by using levelized Cost method of Moran.

The cost rate

$$\dot{C}[\$ \text{ per year}] = [PEC - (SV)PWF(i, n)CRF(i, n)] \quad [40] \quad Sv = 0.1 \quad PEC = 4122 \left[ \frac{\dot{M}g(h_{in} - h_{out})}{18\Delta T_{imaph}} \right]^{0.6} \quad [40]$$

$$\Delta T_{imaph} = T_1 - T_0 = 431.51K \quad h_{out} = \frac{1}{ds} = 0.0023 \text{ } kJ^{-1}K \quad PEC = 4122 \left[ \frac{\dot{M}g(h_{in} - 0.0023)}{7767.36} \right]^{0.6} \quad PWF(i, n) = (1 + i)^{-n} \quad CRF(i, n) = \frac{i}{1 - (1 + i)^{-n}}$$

$$\dot{C}[\$ \text{ per year}] = PEC - \frac{0.1(1 + i)^{-n}}{1 - (1 + i)^{-n}} = 4122 \left[ \frac{\dot{M}g(h_{in} - 0.0023)}{7767.36} \right]^{0.6} - \frac{0.1(1 + i)^{-n}}{1 - (1 + i)^{-n}}$$

$$\text{The energy cost rate of the heating compartment} = 4122 \left[ \frac{\dot{M}g(h_{in} - 0.0023)}{7767.36} \right]^{0.6} - \frac{0.1(1 + i)^{-n}}{1 - (1 + i)^{-n}} \quad \$/\text{year}$$

#### 6.0 Conclusion

The heating compartment is able to raise the energy of air by 433.6776 kJ/Kg at the same compressed pressure; therefore the efficiency of compressed air turbine is being optimized by the addition of a heating compartment. The circular geometry was chosen to accommodate thermal expansion and contraction and to minimize heat lost. It is also noticed during simulation that there is a gradual decline in pressure of air over time. Although, this retardation in minima but it could accumulate to huge over a long working

period. Therefore the heating compartment should idle period during working operations of an air turbine. Researches can be to bring a method or methods to eliminate this effect and increase the efficiency of an heating compartment in air turbine application.

## References

- [1] Meenakshisundaram Arulkumaran & William Christraj (2012). Experimental Analysis of Non tracing solar Parabolic Dish concentrating System for Steam Generation. Engineering Journal vol 16 Issue 2 doi:[10.4186/ej.2012.16.2.53](https://doi.org/10.4186/ej.2012.16.2.53)
- [2] Prateek Rohatgi, Kehinde Alare & Taiwo Alare (2020). Renewable Energy. Inventors Domain Group Presentation. Doi:44
- [3] Taiwo Alare (2020). Efficiency and Thermoeconomic Optimization of Solar Powered Steam Turbine and Boiler. Research proposal Preprint. Researchgate. Doi:[10.13140/RG.2.2.27101.1321](https://doi.org/10.13140/RG.2.2.27101.1321)
- [4] Falcao et al. (2012). Air turbines. Comprehensive Renewable Energy. Doi: [10.1016/B97-0-08-087872-0.00805-2](https://doi.org/10.1016/B97-0-08-087872-0.00805-2)
- [5] L. M. C. Gato and A. F. O. Falcao, “Aerodynamics of the wells turbine,” International Journal of Mechanical Sciences, vol. 30, no. 6, pp. 383–395, 1988.
- [6] L. M. C. Gato and A. F. O. Falcao, “Performance of the Wells turbine with a double row of guide vanes,” JSME International Journal II, vol. 33, no. 2, pp. 265–271, 1990.
- [7] M. Inoue, K. Kaneko, and T. Setoguchi, “Studies on Wells turbine for wave power generator (part 3; effect of guide vanes),” Bulletin of the JSME, vol. 28, no. 243, pp. 1986–1991, 1985.
- [8] M. Inoue, K. Kaneko, T. Setoguchi, and S. Raghunathan, “Simulation of starting characteristics of the Wells turbine,” in Proceedings of the AIAA/ASME 4th Fluid Mechanics, Plasma Dynamics and Laser Conference, AIAA-86-1122, Atlanta, USA, 1986.
- [9] M. Inou, K. Kaneko, T. Setoguchi, and K. Shimamoto, “Studies on Wells turbine for wave power generator (part 4; starting and running characteristics in periodically oscillating flow),” Bulletin of the JSME, vol. 29, no. 250, pp. 1177–1182.
- [10] M. Inoue, K. Kaneko, T. Setoguchi, and T. Saruwatari (1988). Studies on the Wells turbine for wave power generator (turbine characteristics and design parameter for irregular wave). JSME International Journal II, vol. 31, no. 4, pp. 676–682.
- [11] K. Kaneko, T. Setoguchi, and M. Inoue (1986). Performance of Wells turbine in oscillating flow. in Proceedings of the Current Practices and New Technology in Ocean Engineering, vol. 2, pp. 447–452, ASME, New Orleans, La, USA.

- [12] S. Raghunathan (1995). The wells air turbine for wave energy conversion. *Progress in Aerospace Sciences*, vol. 31, no. 4, pp. 335–386, .
- [13] S. Raghunathan and C. P. Tan (+982). Performance of Wells turbine at starting. *Journal of Energy*, vol. 6, pp. 430–431
- [14] S. Raghunathan, T. Setoguchi, and K. Kaneko (1989). “Effect of inlet conditions on the performance of Wells turbine,” *Journal of Energy Resources Technology*, vol. 111, no. 1, pp. 37–42,
- [15] T. Setoguchi, K. Kaneko, and M. Inoue (1986). Determination of optimum geometry of Wells turbine rotor for wave power generator aqanerator (part 1). in *Proceedings of the Current Practices and New Technology in Ocean Engineering*, vol. 2, pp. 435–440, ASME, New O rleans, La, USA,
- [16] Manabu Takao and Toshiaki Setoguchi (2012). Air Turbines for Wave Energy Conversion. *International Journal of Rotating Machinery* Volume 2012, Article ID 717398, 10 pages  
Doi:10.1155/2012/717398
- [17] U.S. Department of Energy (2003). Improving compressed air system performance, a source book for industry.
- [18] Van Ormer, Hank. (1995). Optimize your plant’s compressed air system. *Chemical Engineering Progress*, 91(2):35-39
- [19] Foss, R. Scot. (2005). Optimizing the compressed air system. *Energy Engineering*, 102(1):49-60
- [20] Sheckler, Mark S. (2007). Assessment of a Compressed air system. *Energy Engineering*, 104(1):13-22
- [21] Dalgleish, A.Z. & L.J. Grobler. (2006). Energy management opportunities on a compressed air system in a packaging facility. *Energy Engineering*, 103(4):42-52
- [22] Hussam S. Dheyab, Manar Salih Mahdi Al-Jethelah1,Tadahmun Ahmed Yassen, Thamir Khalil Ibrahim (2019). Experimental Study of The Optimum Air Gap of a Rectangular Solar Air Heater. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 59, Issue 2 (2019) 318-329
- [23] Tabish Alam, R.P. Saini, J.S. Saini (2014). Heat and flow characteristics of air heater ducts provided with turbulators—A review. *Renewable and Sustainable Energy Reviews*, Volume 31,pp289-304.  
<https://doi.org/10.1016/j.rser.2013.11.050>.
- [24] Ahmad, A., J. S. Saini, and H. K. Varma. (1996). Thermohydraulic performance of packed-bed solar air heaters. *Energy Conversion and Management* 37:205–214.
- [25] I Akpınar, E. K. and F. Koçyiğit. (2010). Energy and exergy analysis of a new flat-plate solar air heater having different obstacles on absorber plates. *Applied Energy* 87:3438–50.
- [26] Alta, D., E. Bilgili, C. Ertekin, and O. Yaldiz. (2010). Experimental investigation of three different solar air heaters: Energy and exergy analyses. *Applied Energy* 87:2953–73.

- [27] Aoues, K., N. Moummi, M. Zellouf, and A. Benchabane. (2011). Thermal performance improvement of solar air flat plate collector: A theoretical analysis and an experimental study in Biskra, Algeria. *International Journal of Ambient Energy* 32:95–102.
- [28] Cheng, K. C. and M. Akiyama. (1970). Laminar forced convection heat transfer in curved rectangular channels. *International Journal of Heat and Mass Transfer* 13:471–90.
- [29] Close, D. J. (1963). Solar air heaters for low and moderate temperature applications. *Solar Energy* 7:117–24.
- [30] Cortés, A. and R. Piacentini. (1990). Improvement of the efficiency of a bare solar collector by means of turbulence promoters. *Applied Energy* 36:253–61.
- [31] Duffie, J. A. and W. A. Beckman. (1991). *Solar Engineering of Thermal Processes*. 2nd ed. New York: John Wiley & Sons.
- [32] Eicker, U. (2003). *Solar Technologies for Buildings*. Chichester: John Wiley & Sons.
- [33] El-Sebaei, A. A., S. Aboul-Enein, M. R. I. Ramadan, S. M. Shalaby, and B. M. Moharram. (2011). Investigation of thermal performance of double pass flat and v-corrugated plate solar air heaters. *Energy* 36:1076–86.
- [34] Garg, H. P. and R. S. Adhikari. (1999). Performance evaluation of a single solar air heater with N-subcollectors connected in different combinations. *International Journal of Energy Research* 23:403–414.
- [35] Gill, R. S., S. Singh, and P. P. Singh. (2012). Low cost solar air heater. *Energy Conversion and Management* 57:131–42.
- [36] Gupta, D., S. C. Solanki, and J. S. Saini. (1997). Thermo-hydraulic performance of solar air heaters with roughened absorber plates. *Solar Energy* 61:33–42.
- [37] Bipra Gorai, R.K. Jana, Premchand (2003). Characteristics and utilisation of copper slag—a review. *Resources, Conservation and Recycling*, Volume 39, Issue 4.
- [38] Kyung-Tae Park, Yong-Seog Kim, Jung Guk Lee, Dong Hyuk Shin (2000). Thermal stability and mechanical properties of ultrafine grained low carbon steel. *Materials Science and Engineering: A*, Volume 293, Issues 1–2. pp 165-172. [https://doi.org/10.1016/S0921-5093\(00\)01220-X](https://doi.org/10.1016/S0921-5093(00)01220-X)
- [39] Kevin Graham Harding (2018). *Heat Transfer Introduction*
- [40] Goriji – Bandpy, M et al. (2011). Exergoeconomic Optimization of Gas Turbine Power Plant Operating Parameter Using Genetic Algorithms: A Case Study. *Thermal Science* Vol. 15 no 1 pp. 43-54. Doi: [10.229/TSCI101108010G](https://doi.org/10.229/TSCI101108010G)