Development of the investigation of solar updraft tower in the city of Erbil to the north of Iraq

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Abstract

This work is the result of more than ten years of research in solar tower power plant that has led to five international publications in this field. The investigation started with the work on developing a relation between the size of the components, so that when the system is designed, a more feasible outcome can be achieved. In the next stage the collector area limitations were studied and for that purpose the capacity of the collector was reduced to one third and the sides were sealed in a rig that was built for this purpose. The loss of thermal volume due to a smaller collector was compensated in the next stage by introducing thermal concentration with the help of a sun tracking mirror that reflected the solar thermal radiation on the tower base. The work was partially hindered when the School Administration decided to destroy the rig. Fortunately, sufficient data was collected to finish this stage. In the next stage a simulation model was developed to look into the ability of such a device to adapt to alpine terrain which is an attribute of local landscape. The model was verified and used to run a parametric study. The system performance was compatible but lower than the conventional flat configuration. In the final stage a turbine was designed for the system using a different airfoil profile. The model was verified but could not be integrated into the simulation for the whole system. The misgivings of the reverse fan model were outlined when compared to the turbine. The reverse fan model was assembled into the developed sloped collector solar tower model and used to investigate the performance of the overall system. The system was functional with reduced capacity.

Keywords: Solar, Updraft tower, geometry, thermal concentration, sloped collector, turbine

1. Introduction

Historically, Iraq has been largely dependent on fossil fuel for meeting its energy needs. The move towards renewable energy has started but it is caught at a slow pace on a lengthy freeway. Until now hydropower has been the only significant contributor however its role has been affected by the annual precipitation, irrigation, drinking and industrial demands, imposed on dams and reservoirs (Our World in Data, 2022).

An enduring energy source of high potential in the region with extensive effectiveness duration, scoring a minimum of 8 hours at 8 degrees elevation in December and substantial intensity, exceeding 8.5 kWhr/m^2/day in June, is solar energy, Fig (1), (NASA, 2023) and (University of Oregon, 2023). Eight degrees elevation corresponds to 08:00 hrs, marking 49 minutes after sunrise and 16:00 hrs, indicating 53 minutes before sunset, on December 21st which is the shortest day of the year for latitude 36.18 and longitude 44.01 matching the considered location within the limits of the city of Erbil to the North of Iraq. The fact that grid electricity has not been able to meet the load demand has historically pushed the authorities to rely for varying amounts of electricity, according to the time of day and season, on large diesel district generators. They usually reconnect the electricity after grid failure with custom amounts of power, sold in cash per Ampere for as high as 10 to 15 times the public tariffs. Increasing evidence of decentralized solar energy systems on roof tops and more recently centralized public utilities are becoming more mainstream in the Norther region (Gov.krd, 2023).

In solar updraft tower thermal energy is used to stimulate density change and air movement over a turbine, leading to electricity generation. Solar updraft tower also known as solar tower is composed of primarily a solar collector with the specific task to heat the air beneath it. The second component in this system is the tower, usually placed at the center of the collector. The tower is mostly vertical but can be designed to match the surrounding terrain, be divergent or even float in the air (Zhou, 2009). The third component is a modified air turbine, usually placed inside the tower near the base.

Using solar thermal effects to generate air currents and channeling this synthesized wind to pass over a turbine in a controlled environment inside an updraft tower, form a potential alternative worthy of research to support the existing

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renewable resources in the region. When considering the main requirements of solar updraft tower power plant against the Iraqi arid climate and type of terrain, including the region to the north of the country where the city of Erbil is, there is sufficient justification for the development of this concept through investigation and experimental work. Solar updraft tower has also been projected as a hybrid system with supportive roles in air purification, water desalination, drying in agriculture and co-generation with photovoltaics (Huang, 2020), (Tawalbeh et al., 2023) and (Xie et al, 2022).

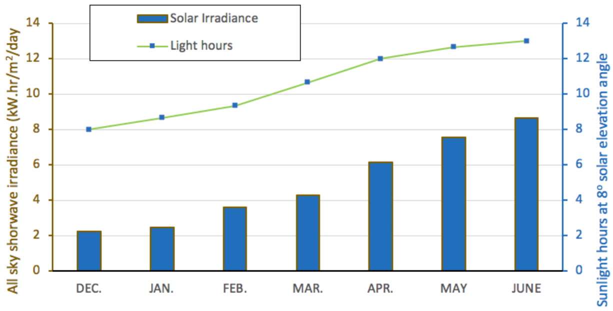

Figure 1: Solar irradiance and sunlight hours for Erbil from Dec. 2021 to June of 2022 at 8 degrees solar elevation

This work is comprised of consecutively reviewing selected literature relating to different aspects of solar chimney, also known as the solar updraft tower. The review connects between research projects in complementing fields of solar updraft tower, planned by the author and performed with research partners and teams. This document is based on five international publications where this researcher has taken over the role of the corresponding author and four academically assessed documents, under his supervision. Throughout this work, there is a candid tendency to refer to the obstacles and challenges. It is an attempt to visualize a more comprehensive reflection of what these endeavors contained. The aim is to motivate researchers to strengthen strive for reaching workable solutions and accredited recognition.

2. Modeling for a geometrical relation

Study of the geometry of the system defied the classical boundaries through adjustment and improvement of mathematical models. In an interesting work, solar tower geometry was investigated using a dimensionless model. The model proved successful with more realistic results for the pressure at the bottom of the tower and air flow enhancement (Okada, 2015). Research on improvement of the dimensional layout of the plant continued on a different note with the development of an unsteady simulation model. This investigation suggested a direct relation between the tower height and the system output represented by the generation efficiency and stability (Li et al., 2016). The relation between the ratio of geometry constraints of the main components was investigated within a merged convective axisymmetric domain. The results suggested a combined approach to estimation of collector and tower variables strongly affected by the ground heat storage (Vieira et al., 2017). In another attempt to reach an optimal geometrical configuration, the collector was slightly tilted in a converging cast. Thermodynamics of air flow was investigated using a turbulence model and CFD simulation. Flow regimes at the tower base were studies with emphasis on the development of pressure, temperature and velocity profiles. It was concluded that the increase of collector slope, convergence angle and radius created noteworthy improvements in performance (Fu, 2019).
Nearly ten years of research in solar updraft tower started with an experimental project and basic conceivable goals. The preliminary experimental work resulted in building the first model and then working on applying improvements in terms of the covering material and establishing a variable collector slope. Unfortunately, the experimental targets set for the model in Fig. (2) were not realized due to financial difficulties in 2014. However, the unfinished experimental work maintained a parallel course with an adjusted proposal looking into modeling and the relation between the geometrical components of the system (Mohammed, 2019).

Figure 2: Different stages of construction for the unfinish model (2) hindered by terminal difficulties. (a) Motion support on the circumference (b) Angle adjustment (c) Lifting mechanism (d) Polycarbonic cover (e) Installation of the cover

A steady state, two-dimensional, axisymmetric model was constructed for the system, working through an incompressible flow with homogenous heating and uniform streams inside the collector and no peripheral currents or temperature gradient in the tower. The properties were fixed except for density which was obtained from the Boussinesque approximation. These assumptions were applied to continuity, momentum, energy and standard turbulent ($k - \epsilon$) model (Ming et al., 2017). Ansys Fluent was used for designing the structure and modeling the flow and heat transfer inside the collector, tower and the absorber layer. After testing a range of different element lengths, a mesh size of 0.9 m (leading to 1,294,321.00 elements) was selected based on the stability of results.
The velocity and temperature results were compared with experimental data from Manzanares (Haaf, 1983) and the obtained Rayleigh numbers were checked against similar works in literature with reasonable agreement (Tahar and Mahfoud, 2013). Over 180 cases were tested within 15 groups to find similar patterns at different collector and tower dimensions so that to suggest the most appropriate matching. Figures (3) and (4) show the relations graphically and can be used to select in between values.

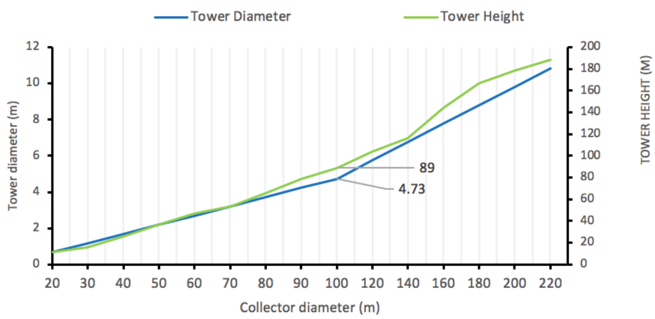

Figure 3: Relation between collector diameter and tower “height and diameter” for optimized performance

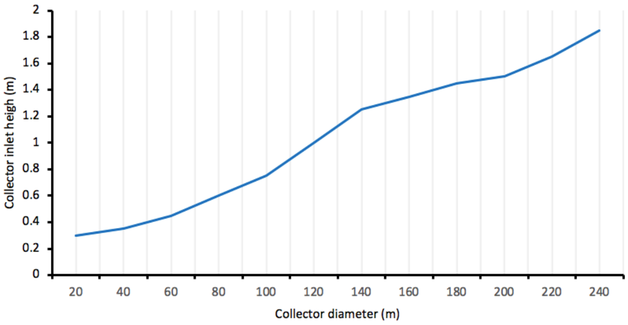

Figure 4: Relation between collector inlet height and collector diameter for optimized performance

3. Experimental work with restricted geometry

Eighty years after Isidoro Cabanyes, the most significant evidence of solar tower principle employed for power generation was up and running in a different part of Spain. The power plant in Manzanares was the living evidence that there is power to be made from solar tower. The next section is prepared as a brief review over the recent experimental works and geometrical modification related to solar tower power plant.
The experimental work found new momentum as researchers attempted to explore the geometry and investigate the effect on the performance. A group of researchers in Fukuoka - Japan constructed and developed a numerical model for a divergent tower and applied a parametric approach to study the divergence angle and tower height. They

suggested a slope of 4 degrees for optimum results working with a tower of 2 m height (Ohya et al., 2016). Looking into it from a different angle, a group of researchers in Edirne – Turkey experimented with a perforated collector of 10 m radius and closed periphery inlet. They called it; transpired solar collector with 35% collector area perforation and a tower height of 16.5 m. Air was allowed to enter the heating space from the collector top. They ran the system in winter and summer and observed higher efficiencies reaching a maxim temperature difference of 18 ºC (Eryener et al., 2017). And in another work, a group of researchers from Tafresh – Iran, measured the thermal performance of three collector configurations in indoors environment, using four artificial sources of thermal energy on a 100:1 scale model of the Spanish rig. The normally sloping (divergent) layout achieved the highest temperature difference and air flow velocity in the system (Mehdipour et al., 2020).

The idea of this work (Khalid and Atrooshi, 2020a) which represents the third generation of development on the original rig geometry was born out of the concern over the land restrictions. However, there were other factors that led to this design such as cost, availability of material, weather effects and funding. Two aspects were considered. One was the collector size and the other; the physical boundaries surrounding the allocated location. An experimental rig was designed and constructed as in Fig. (5) with the collector; one third the size of a normal circular shape. The sides where sealed and air was allowed only from the frontal inlet which was positioned to face south. The tower base was adjusted to accommodate the collector shape and the collector was divided into (16) sections with each section made up of (7) rows. Collector diameter was (19 m) and tower height (7.35 m).

Figure 5: Showing the experimental rig when the collector was shape. (a) Front view of the rig showing the air inlet area (b) Side view showing a sealed side

Temperature readings were collected from (12) sensors connected to a data logger. The sensors were installed along the collector radius, in the transition zone and over the length of the tower as shown in Fig. (6). Additionally, ambient air, ground and collector surface temperatures were also recorded. Airflow inside the tower was measured by a GM8901 anemometer so was the thermal solar radiation using a Hukseflux LP02 pyranometer. Calibration, error estimation and uncertainty analysis were applied to the instruments.

Narrowing collector section towards the tower base and sealing the collector sides against air flow, affected the development of temperature profile and created a gap between the glass and ground. Temperature readings for a typical day are complemented by solar radiation and airflow velocity in Fig. (7). The diagram shows that both temperature and velocity peak simultaneously for this particular geometry and while solar radiation reaches its highest value at mid-day, the highest ambient temperature is reached around two hours later.

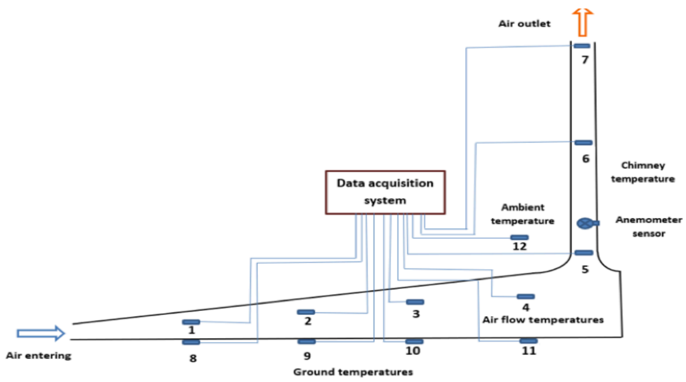

Figure 6: Instrumentation layout for the test rig

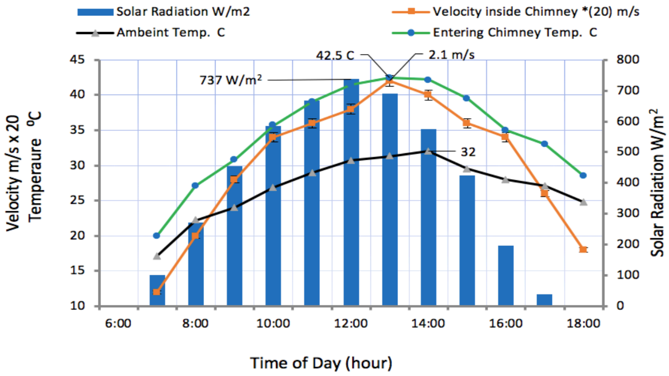

Figure 7: Hourly readings for ambient air temperature, air temperature at tower inlet, solar radiation and airflow velocity for October 7, 2017

4. Solar thermal concentration effect

Regardless of the amount of optimization, any reduction in collector surface area will have implications on the thermal performance of the system. In order to balance this act, the solar exposure intensity on the system should be enhanced through a suitable mechanism. One way for achieving this goal is by introducing solar thermal concentration. There are limited practical examples of such systems but a review over a few recent attempts in this category has been included to outline the progress in this field before describing the development of the concept in Erbil.

Following a very similar goal, solar thermal concentration was channeled by two intensifiers and an air sink, working with a small model. Obtained data was used to verify an assembled simulation model using SIMPLE and RNG turbulence model inside Ansys Fluent. They concluded that the thermal concentration effect benefited the system with improved air flow characteristics (Shahrezan and Imani, 2015). A few years later another group of researchers experimented with solar thermal concentration inside an experimental unit. They used adjustable mirrors to manually reflect solar radiation on the collector surface using a heliostat model. The outcome indicated enhancement in thermal performance and generated higher airflow rates inside the tower (Hussein and Al Sulaimani, 2018).

The motivation for this work (Khidir and Atrooshi, 2020b) came from the need to overcome the thermal incapacity of a collector reduced to one third of its volume as explained in the previous case. It was an experimental investigation involving a tracking reflector supported by a numerical code based on energy conservation equation developed in Matlab. The reflector was a flat mirror 1 x 1.6 m assembled into a tracking mechanism supported by two DC motors for daily and seasonal adjustments, Fig. (8 a, b, c, and d). The reflector was placed to the north of the system in a position to access the base of the tower.

The reflector mirror had a vertical configuration which allowed a small incident angle and the optimum performance was expected in the morning when the cosine of the angle had a large value. As the sun went up in the sky the angle between the vertical to the plane and the sun beam increased leading to dispersion of the reflected beam and difficulty in staying focused on the target. During data collection, bias, systematic and precision errors were used to verify and explain the deviations (Coleman and Steele, 2009).

Once the reflected beam hit the tower base it went through the transparent polycarbonate layer across the confined air and over to the absorber plate. Heat transfer mechanism between the reflector plate and the absorber layer is based on energy balance equations assuming quasi-steady state conditions (Tiwari and Shyam, 2016). The total area was divided into segments with boundary conditions and preliminary assumptions in Matlab.

Figure 8: Different views of the solar concentration system showing the solar reflection. (a) Reflector and the tracking mechanism from the side (b) Reflector front view supported from behind (c) Reflection of solar thermal radiation on the tower base (d) Front view of the system with collector extending towards south

Probably the most significant of these is the temperature rise due to the concentration effect. Fig. (9) shows the role of the concentrator reflector in enhancing the temperature rise at the tower base for January 2018. The highest effect is observed between 09:00 to 13:30 hours. At its peak, the concentration effect created 10.25% increase in the maximum obtainable temperature. Incident angle is the assembly of a number of solar angles, including altitude which refers to the elevation of the sun during the day and azimuth which is the deviation from north-south plane. Air flow inside the modified collector is still dominated by the density gradient driven by the temperature change. However, it is subject to different constrains. Due to the closed sides, the flow of air is more longitudinal than radial. This is similar to a channel flow with frictional effects from four sides. Fig. (10) shows the profile of airflow for typical days in January and April of 2018. The peak velocity is observed at mid-day with a maximum improvement of 22.2% due to the concentration effect.

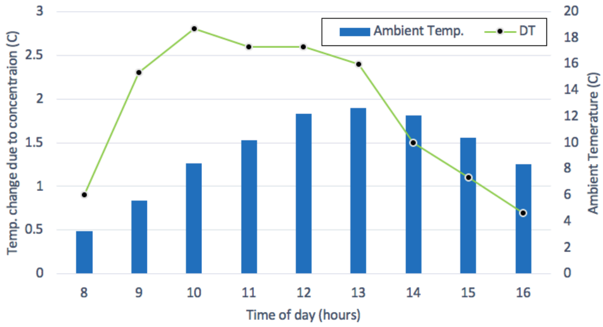

Figure 9: Hourly temperature change at the tower base due to the concentration for a typical day in January

The experimental rig was to continue to provide valuable data for the remaining months of 2018, namely August to December and there was a plan to integrate the assembly of a small turbine into the rig. Unfortunately, on August 18, 2023 this effort was permanently interrupted by the decision of School of Engineering Administration to destroy the rig, Fig. (11). This act ended the experimental journey; however, it did not impede the motivation but on the contrary it became the inspiration for improvement in conveying the scientific message and from then on research relied on modeling and simulation.

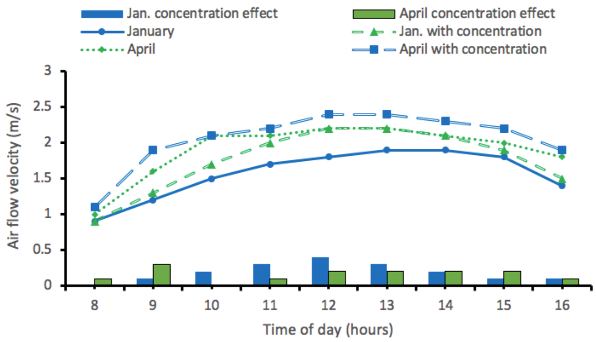

Figure 10: Hourly airflow change at tower base showing the concentration effect for typical days in January and April

Figure 11: Destruction of the experimental rig before the end of the study

5. Adaptation to the landscape with sloped collector

One of the main requirements of any solar tower power plant is a collector of any shape to create the sufficient temperature and density difference at the base of the tower. In locations where the available land is mountainous there are restrictions on construction of large size collectors. One way to overcome this difficulty is by adapting to the existing nature of the land.

The slope of the collector roof was investigated by a group of researchers from Sfax, Tunisia, who used a numerical model in Ansys Fluent and a small experimental solar tower. They studied the effect of changing the collector roof height on the main performance parameters such as temperature, airflow and pressure under local ambient conditions. They concluded that reduction of collector roof height and inlet opening will lead to improvement of outlet power (Ayadi et al., 2017). These results were partially challenged by another investigation that employed a three-dimensional model to look into the tower height and collector slope. The researchers from Telangana, India, concluded that increasing the collector slope leads to enhancement of airflow rate while the temperature inside the collector reduces due to this change (Das and Chandramoh, 2018). Collector slope angle was also investigated by a team of researchers from Algeria. In their research they experimented with the collector entrance slope using a two-dimensional axisymmetric model. They simulated the system performance and concluded that the optimal slope depends on the sloping distance (Kebabsa et al., 2020).

Collector slope may relate to different aspects of the collector shape but so far it has been used extensively to indicate collector roof gradient. In this fourth case, (Weli et al., 2021) the intention was to use the landscape slope as the indicator and run the collector roof slope parallel to it, Fig. (12), to model the natural landscape in the research area. Numerical simulation was developed in Ansys Fluent for steady, three-dimensional, axisymmetric, incompressible flow with Boussinesque approximation for density. Solution of Navier Stokes equations was based on coupling pressure and velocity. Discretization was applied in the process of solving continuity, energy and momentum equations.

The obtained performance figures from this model were comprehensively compared with other works. The noted differences were considered acceptable and validated the developed model for the next stage in which the model was adjusted for the sloped collector geometry. An initial collector slope of (35 degrees) will impose (70 m) reduction in tower height if the overall height of the system is to be kept at (194.5 m) and reduce the horizontal span by (22 m) to (100 m). In this work collector angle was used synonymously with ground slope. Fig. (13) shows the change in tower height and collector horizontal span relative to ground slope angle when overall system height and collector span are kept at (194.6 m) and (244 m) for comparison with the Spanish rig.

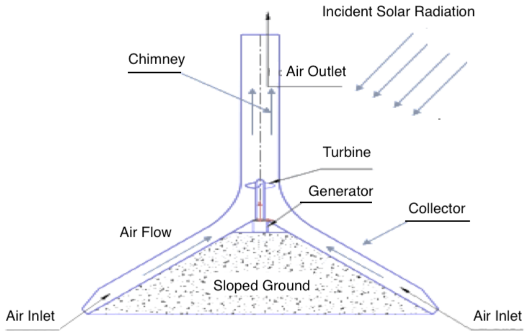

Figure 12: Sloped collector solar tower power plant

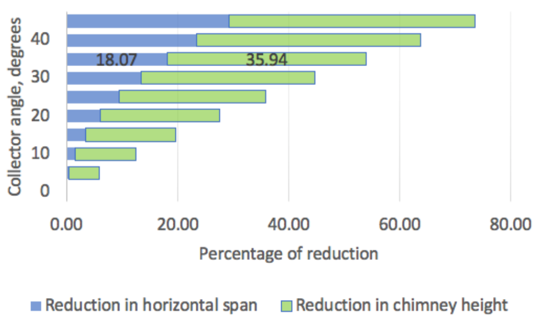

Figure 13: Effect of ground slope angle on system dimensions

In order to investigate the thermal performance of the system it was decided to start with verification of the optimum slope angle for the collector during the period from January to September. The reference point was zero slope at zero surface azimuth angle, facing south. The negative slope referred to inclination on the collector side facing north and the projection of tower shadow was not considered in this work. Solar radiation data from typical days in January, March, July and September at solar noon and different slope angles suggested (35 degrees) as the optimized angle, Fig. (14).

This concluded the requirements for the simulation of the sloped model with dimensions similar in layout to the Spanish rig composed of 1,631,824 nodes and element mesh size of (0.6 m). This model was then used to check the variation of the main performance parameters; temperature, airflow velocity and pressure change along the radial stretch of the sloped collector. The sloped collector solar tower was lagging behind the conventional system by up to 43.14% in airflow velocity and 40.9% in maximum obtainable temperature.

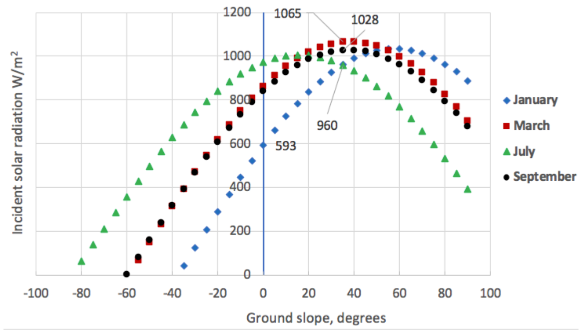

Figure 14: Incident solar radiation during different months of the year at different collector slope angles

6. Development of the turbine effect

Turbine is an essential component in any solar updraft tower system. Without the turbine the arrangement will turn into a natural ventilation system, still very beneficial but not effective for power generation. Turbines in solar towers are different from open access, horizontal or vertical axis wind turbines and the shape, size and position of these turbines have been the subject of research for many years.

The Spanish rig represented the first real manifestation of a turbine inside a solar tower. The confinement inside the tower and the synthesized wind made for a modest upper limit airflow of 9 – 15 m/s but at the same time provided for up to 12.5% higher pressure difference than the conventional wind turbines, allowing for an estimated turbine efficiency of 83% (Haaf et al., 1983). The deployed turbine was positioned at the bottom of the tower and was accessed through guided vanes. The rotor, composed of four adaptable blades was based on glider design with FX W-151-A blades made of composite material, preferably utilizing up to 80% of system overall pressure drop (Schlaich et al., 2005).

The position of the turbine inside the power plant was investigated by a group of researchers from Rize, Turkey. Pressure change which relates directly to the output power of the system was evaluated along the path of airflow. They recommended to use the obtained pressure pattern to find the optimal airflow position and place the turbine there (Cuce et al., 2020). A new design for the turbine inside the updraft tower was studied by a team of researchers who based their approach on the axial flow in the rotor, descending from hydraulic turbine and pump impeller designs. The results revealed that based on this design the system output is less affected by the rotor speed (Zuo et al., 2021). The role of guide vanes was investigated by researchers from India. In this experimental work they compared between the performance the system with and without the vanes. They reported up to 10% improvement when the guide vanes were implemented (Das and Chandramohan, 2022).

In this final case the focus is on the turbine inside the tower (Bakir et al., 2023). The mathematical model for the turbine design was based on blade element momentum theory. The calculation procedure was iterative and aimed to check on design parameter such as chord length, relative flow angle and the twist angle (Manwell and McGowan, 2009). The selected airfoil was NACA 4412, selected for superior performance at low rotational speeds (Yossri et al., 2021). A numerical model was constructed in Matlab. The calculation process was based on assumed values for induction factors leading to local speed ratio. The results were validated in comparison with open-source QBlade software (Marten and Wendler, 2013) and examples from literature including (Khaled et al., 2017).

The above turbine model was assembled to the solar tower simulation model developed in the previous case (Weli et al., 2021) and compared with a number of examples from literature. The developed turbine model proved that optimizing design parameters can indeed allow fruitful results in terms of performance. However, it was not possible to fit this model into the intended sloped collector due to integration and convergence issues. The next available

option was to use the reverse fan model. Despite the observed deviations, the reverse fan model was the available option to be employed inside the sloped collector solar tower due to time limit restrictions.
In the concluding sections the performance of the overall sloped collector solar tower power plant was studied. The configuration is as shown in Fig. (12). The sloped collector behaves independently from other settings. The impact of the pressure change imposed by the reverse fan model was tangible for both temperature and velocity, Fig. (15).

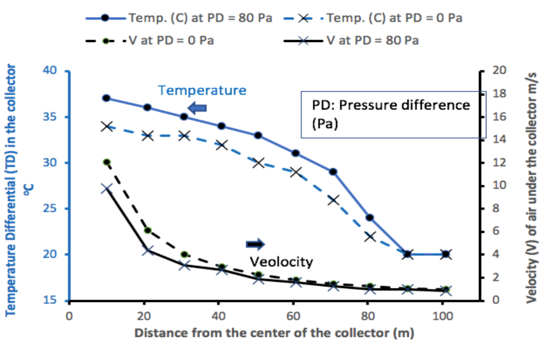

Figure 15: Velocity and temperature change along the radius of sloped collector solar chimney

A maximum temperature difference of nearly (3° C) was imposed by the turbine effect, near the entry to the tower. The pressure reduction due to the turbine effect led to an increase in airflow velocity, peaking near the tower at (12 m/s), almost (2 m/s) higher than when there was no reverse fan effect. The limit for turbine pressure-drop in the sloped collector solar tower power plant was set at (120 Pa), Fig. (16). Beyond this threshold the system became unpredictable. The recommended range of pressure-drop for turbine operation in a plant of this configuration and size is between (80 to 100 Pa).

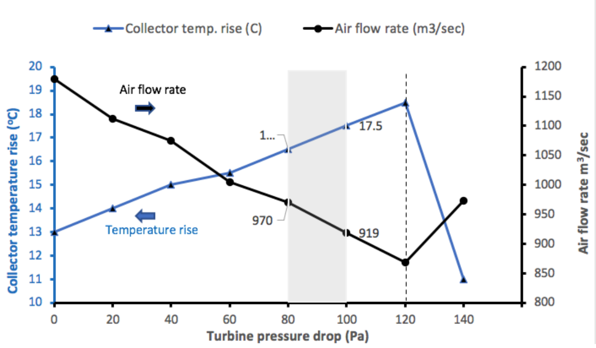

Figure 16: Effect of turbine pressure drop on collector temperature and airflow rate

7. Conclusions

This work reviews the different phases of the dedicated research work on solar tower power plant in the academic scene of the city of Erbil to the North of Iraq. The manuscript trails the achievements of five published articles in relevant international journals. Case one was developed to optimize the meshing of geometry for the different components of the system. Relations were developed to suggest the best match. Case two was experimental and worked on one-third the circular collector size. Performance of the system in terms of temperature, pressure and airflow velocity was of prime value due to the unique shape. Case three was applied to compensate the reduction of the thermal performance of the system with solar concentration. Hourly data were collected for temperature and airflow velocity and the effect of solar angles on temperature rise was recorded. The collection of data was interrupted with the decision of the School Administration to destroy the rig! Experimental work was discontinued indefinitely but modeling was adopted to support the remaining work. In the next case a sloped collector solar tower power plant was modeled with Ansys to look into the adaptation of the collector to the landscape in the research area. The results were compatible but suffered 43.14% in airflow velocity. In the final case the focus was on the turbine and a model was designed starting from the airfoil. A reverse fan configuration was compared with this model and despite its drawbacks it was used to run a parametric study on the sloped collector solar tower system. Both temperature and airflow velocity interacted with the pressure reduction in the turbine scoring (3° C) and (2 m/s) decrease. While the concept of solar updraft tower is still being intensively investigated, bold action is required to deliver it to the next stage.

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