PERFORMANCE ANALYSIS OF SOLAR CHIMNEY POWER PLANT (SCPP): A CFD APPROACH

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I, Ayush Saraswat, Roll. No. 2K20/THE/06 of M. Tech (Thermal Engineering), hereby declare that the project Dissertation titled "Performance analysis of Solar Chimney Power Plant (SCPP): A CFD approach" which is submitted by me to the Department of Mechanical Engineering, Production & Industrial and Automobile Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project titled "Performance analysis of Solar Chimney Power Plant (SCPP): A CFD approach" which is submitted by Ayush Saraswat, Roll. No. 2K20/THE/06 Department of Mechanical, Production & Industrial and Automobile Engineering, Delhi Technological University, Delhi in the partial fulfillment of the requirement for the award of degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

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ABSTRACT

The solar chimney's design is getting innovative solutions and modifications from quite a decade because of the importance the mechanism has proven out. The first solar chimney power plant was established in Manzanares, Spain in early 1980s with an aim of studying its power generation capacity. Since then, the system has caught attention of many researchers because of its simple design and working. The SCPP (Solar Chimney Power Plant) has quite the unique working for power generation which happens with the combined effect of greenhouse and buoyancy effect experienced by the warm air in collector area of the SCPP.

This present study focused on testing the potential of SCPP if it's established in Indian cities where it can help meet low scale electricity demands. The 3 Indian cities chosen are the Ladakh, Mahendragiri and Kutch. The choice has derived from the idea to check CFD modelling and the results from solutions to compare the power generating capacity and the output velocity which these models can offer.

The CFD modelling was validated with the other works in CFD from other scholars who validated their simulation results from the experimental data and found very little variation in values. After the successful validation of the 3D CFD modelling, it can be said that despite being a colder place for almost all time of the year, the potential at Ladakh is quite impressive. Mahendragiri in Odisha showed good results due to the fact, the location falls in the tropical zones of Indian subcontinent which benefits it with the direct sunshine for longer hours.

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CHAPTER 1: INTRODUCTION

1.1. ENERGY SCENARIO WORLDWIDE

With the growing consumption of electricity in our daily life, the production of energy is taking a heavy toll on the use of fossil fuels. Fossils fuels specially like coal has been known to mankind since centuries. It found it's primary use since 1800s in heating homes in colder areas. When fossil fuels were in initial phase of being used by small amount of population, the pollution and its adverse effects were unknown. With the growing technologies and advancements, it has become evident that the continuous usage of fossil fuels is causing a lot of harm to the environment in which we and other organisms live. Besides, these natural sources of energy are being depleted with quite an alarming rate. With the growing understanding of conserving and preserving our environment, the research work on renewable sources of energy has picked up the interest of many scholars around the globe.

Conventional sources of energy like coal, natural gas, oil are the ones which are causing harm to our environment and causing many issues like global warming, human's respiratory issues, acid rain and much more. Awareness regarding the use of renewable sources of energy available locally is also pushed and promoted by many governments worldwide to shift the dependency from conventional and non-renewable sources of energy. The available renewable sources of energy to us are wind energy, solar energy, geothermal energy, biomass energy and hydro power.

With the recent trends of technology inclining towards increasing our dependency on electricity as the number of gadgets' collection increasing at a rapid rate, there is definitely a need of looking for an alternative of power generation which can provide a sustainable and reliable way of producing electricity. Though electric cars and electric vehicles curb the air pollution and have proven out to be environment friendly, there still exists a challenge in upcoming future as how the energy demands will be met. Developing countries like India has a huge population and the rapid dependency on electric charged gadgets owned by large population is an early indicator of requirement to shift our focus to available renewable energy sources in the country.

While coals on combustion give rise to harmful gases like CO_2, NO_x and SO_2 etc. The renewable sources of energy do not contribute to the harmful effects like glacier melting in Arctic and greenhouse gases, which provides the confidence to pursue research studies in such areas to enhance the efficiency and output of such systems.

Table 1 shows the recent statistics by M. Garside [1], which shows consumption of coal by leading nations.

Table 1: Global consumption of coal by different countries in 2020

Countries	**Coal Consumption (in 10^{18} joules)**
China	82.24
India	17.52
US	9.1
Japan	4.54
South Africa	3.42
Russia	3.24
Indonesia	3.23
South Korea	3.02
Vietnam	2.05
Germany	1.81
Australia	1.67

From the above information, it’s quite evident that world’s most populous countries like China and India are still consuming coal with higher volumes unlike developed nations like US, Japan, which do consume more power per person than the mentioned countries of China and India.

This is the right time for India to look upon it’s available options to overcome a future burden of huge power generation from conventional and non-renewable sources like coal. It’s very important to explore the solar energy and wind energy potential in India to predict a good sustainable and clean harnessing of energy which is also in favour of our ecological balance to ensure available of energy to most household and citizens.

Table 2. shows the the latest statistics of 2020 to look into the global coal reserves by different countries, provided by Garside. It's evident that despite having largest coal reserves, US is preserving its resources and already trying different ways to harness energy.

Table 2. Global coal reserves of different countries in 2020

Countries	**Coal Reserves (in million metric tons)**
US	248, 939
Russia	162, 164
Australia	150, 224
China	143, 194
India	110, 048
Germany	35, 902
Indonesia	34, 867

From the above data, it's important to understand the role of developing nations like India have to play in order to ensure clean power generation and also sustaining the coal reserves the country has. India has thermal power plants being operated by conventional ways of using the coal. This coal combustion has led to the rise of PM2.5 particulates in air in vicinal areas around the plant and hazardous to the workers and employees staying near such locations.

1.2. ENERGY POLICIES IN INDIA

The main objective of Indian policies based on Energy sector growth is more towards creating a sustainable environment of power production with special attention in reducing energy poverty. With this in mind, the Government of India is seen launching policies which intend to provide subsidy for people opting to choose the instalment of solar power as their source of power at homes and other commercial places. Government of India founded Ministry of New and Renewable Energy (MNRE) in 1992 focusing on nurturing various technologies which uses renewable energy sources and helps the public to have the access in clean and greener future of India. Indian Government launched the foundation of Solar Energy Corporation of India (SECI), a CPSU, in 2011 with an aim to implement the different setups of solar energy throughout the country which can help in saving some expenditure on electricity bills and replaces the dependency on commercially created power from thermal power plants to some extent.

India is said to have the capacity of nearly 4000-6000 kWh solar incident energy [2] every and almost 4-8 kWh / m^2 amount of solar energy available to the ground in India. The application of solar PV cells has increased at a significant rate from past a decade with many farm houses, small agricultural lands using it to carry out their low power requirement work. In a report by National Institute of Solar Energy, around 2-4 % of assumed waste land area is expected to be covered by solar PV modules, which can provide solar potential of up to 750 GW to the country. In January 2010, National Solar mission was launched with an objective of achieving the goals set to handle the global climate change by providing solar power of up to 20 thousand MW by 2022. Various policies have been proposed in this mission in order to promote the use of solar energy in power generation. Some of the policies like Solar Park Scheme, Canal bank & Canal top Scheme, Bundling Scheme, Grid Connected Solar Rooftop Scheme etc. have been addressed to allow the expansion of solar technology throughout the country.

India has tremendously achieved a growth of more than 10 times in expanding its solar power capacity from around 2.5 GW back in 2014 to the latest at 31 GW after the gap of 5 years. The awareness and benefits of solar energy is increasing at a rate that it is expected to attract lots of investors and small business players in market to contribute in its further spread of services throughout the nation.

The implementation and achievement of targets by Government in timely manner has brought a good impression and confidence among solar energy modules' buyers. From the latest reports by the MNRE, it has been shown that around 40 GW of solar power technology has been installed in the country. With the help of Ministry of Power, under the scheme of PM Kusum, the instalments of solar pumps has proven out to be successful and the solar home lights application are being taken care under 'Saubhagya' scheme.

1.3. CURRENT STATUS OF SOLAR POWER GENERATION TECHNOLOGIES

Currently, there exists basically two ways of harnessing power through the solar energy. Use of solar power thermal system is one of the two methods or technology in which the available solar radiation at a location is first collected by various collectors like Parabolic Trough Collector and other types of collectors are used to first capture the solar energy in order to convert it into the heat energy. Then, with the help of different flowing media, the thermal energy is finally generated using thermoelectric power generation techniques. This process of solar power generation is bit similar to the conventional ways of generating electricity.

The second way is what is experienced commercially on large scale, solar PV modules and photochemical power generation. These devices have the necessary tools to directly convert the incident solar radiation into the electricity without much hassle of employing an intermediate process like in former one.

Other researchers are trying to integrate these models with other small changes and different technology to enhance their output and efficiency. Commercialisation of solar PV panels which are responsible for directly conversion of solar energy into electricity via use of battery has been successful throughout the globe. Now, the next step in research work is focusing on finding other ways to use the available solar energy by different techniques which can be sustainable.

1.3.1. HELIOSTAT POWER SYSTEM

These solar powered systems make use of hundreds of heliostats mirrors to collect the solar incident and radiation and then focusing it towards a receiver which is a heat exchanger. The reflected sun rays collected in that heliostat mirrors raise the temperature of working fluid in receiver and hence the heat transfer in it indirectly converts the heat energy into the electric energy. Such devices have shown the capacity to generate the power from 40 MW to 500 MW. US built their first heliostat solar plant in 1980s in Mojave desert, California, which was named as Solar One and later in mid 1990s, it was converted into Solar Two. The systems have the complexity related to the designing which increases its initial cost. The working fluid used mostly in this was water and oil but nowadays it’s a mixture of sodium nitrate and potassium nitrate.

1.3.2. PARABOLIC TROUGH COLLECTOR (PTC) SYSTEM

In this system, the heat is collected from solar radiation and then with line focusing, it’s used to heat the steam, which is used to run the turbine and generate electricity. Comparatively this system is bulkier than other solar collector systems. The main source of heat in this system is a long heat pipeline. One of the important precautions to be kept in mind while planning about this system is that this system offers a high resistance from wind. This characteristic of this system makes it more suitable in areas with lower winds and air velocity. In 2020, IIT Madras [3] developed a PTC for purposes like desalination and power generation for fulfilment of low power requirement industries.

1.3.3 SOLAR PV (PHOTO-VOLTAIC) PANELS

Solar PV modules have found their wide range applications globally in most countries. In India, the more focus is on developing and promoting the solar PV panels at a subsidized price to the public to meet their low to average power demands. In many agricultural places, solar PV panels have found their places among farmers in carrying out irrigation and other pumps related works. One of the challenge farmers in India facing currently are the assurance from manufacturers and proper training services to use such technology for their use. In India, almost all of the solar PV panels are imported from other countries, so setting up the proper infrastructure for services and operations has become quite a stepping stone while dealing with public in Tier-2, Tier-3 cities.

From past a decade, mostly Mediterranean countries and Middle-East regions are working towards improving efficiencies of the solar powered technologies. Most of the research work existing now is at a great pace in the mentioned regions. While India has an abundant source of energy, the research work in the country is lacking in terms of technological advancements in other solar powered technologies. India has a huge potential for solar powered technology and Government of India is also focusing towards replacing some part of the country’s power demands by these solar driven power generation systems.

1.4. SOLAR CHIMNEY POWER PLANT (SCPP)

Still, the today's existing solar technologies aren't able to keep up with power demands that are to be fulfilled. The journey of seeking more and more intuitive ways to develop highly efficient devices and processes for solar energy driven machines is still ongoing. Different techniques and principles are being used to capture and utilise the solar energy incident on huge parts of barren lands.

One of the used new technologies is using solar radiation to generate electricity by a vertical axis wind turbine fixed at the place where air velocity is maximum and a higher pressure drop exists. SCPP is consists of three major parts, which are collector, chimney and a wind turbine. The buoyancy principle finds its primary focus here which supports the action of moving lesser denser medium higher, which in this case is the warm air. The solar radiation passes through the semi-transparent or sometimes transparent medium and it gives rise to the greenhouse gas which in return captivates the warm air and warms it more by also the action of heat flux coming from ground due to the hot ground temperature.

Both these effects drive the warm air trapped in collector towards the side of turbine at the center. The potential and heat energy of air contributes in generation of electrical energy by the mechanical action of rotating wind turbine.

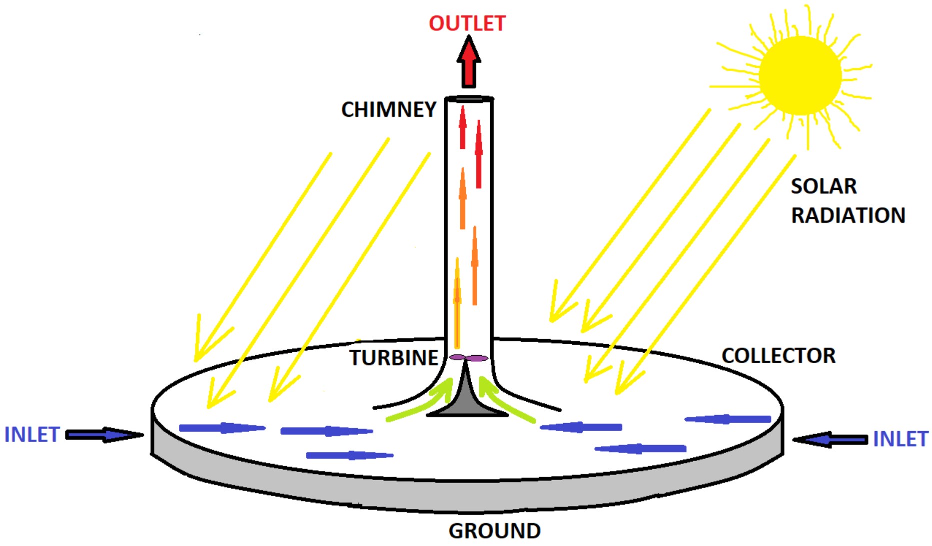

Fig. 1. Schematic diagram of Solar Chimney Power Plant (SCPP)

1.4.1. ADVANTAGES OF SOLAR CHIMNEY POWER PLANT

Harnessing solar energy from any technique is itself very important and necessary specially in current times as it cuts down the dependency of the country on other country's energy reserves. Lots of fossil fuels are being imported by many countries including India to meet their energy demands. Solar energy is present in abundance in Indian subcontinent, which makes accessing and developing technologies related to it easier. India has a desert area and some barren lands, where solar chimney power plants can be setup. The first pilot solar chimney was setup in Manzanares, Spain in 1970s. The area under the collector grew green plants and sustained it, which shows it has an advantage of being setup in a barren place as it can be used to produce electricity as well as it will improve the soil quality and keep ecological balance.

1.4.1.1. LOW INTIAL COST INVESTMENT

Setting up a SCPP, usually requires a large area of land where the collector can be spread from 100 – 400 m. The material of collector is usually polyethylene (PE) or a glass which can trap the low-density air. The turbine is something which requires the initial investment. Chimney can be either of aluminium, alloy or a concrete, depending upon the weight and thermophysical properties of the material and its behaviour under solar radiation. With the establishment of solar chimney power plant, the ground acts as the energy storage layer, which also works during the night by providing warm air when solar radiation is not available. This nature of solar chimney power plant ensures the 24 hours working of the model and power generation at all the time.

1.4.1.2. WORKING FLUID

Air is the only working fluid in the process as it is the only working medium which is easily available in nature in abundance. So, this rules out the dependency of the working of plant on continuous requirement of a working fluid. Air doesn't undergo the phase change which reduces the system's complexity and doing numerical assessment by the researchers. The air pressure is different at different locations, which plays a role in determining the output and power generation of the plant in long run. The plant's working position is yet to be studied under the moisture based tropical and costal places where it's important to see how moisture can affect performance of turbine and the overall plant.

1.4.1.3. SIMPLICITY OF THE MECHANISM

The SCPP working mechanism is simple in a way that the turbine and generator are the only rotating part along with the generator. There isn't any complex machine or part involved. Due to these reasons, the operational and the maintenance cost are fairly low as compared to other power producing solar mechanisms.

1.4.1.4. AVAILABILITY OF MATERIALS

One of the unique things about setting up this plant will be the assurance of availability of raw materials like aluminium, polyethylene, glass and wind turbine, most of these raw materials are available locally. It can easily made available and the establishment would boost jobs and opportunities for locals and businesses.

1.4.1.5. ENVIRONMENTAL IMPACT

Various studies have proven the natural ventilation and air purification achieved by the natural phenomenon which the working of solar chimney follows too. This natural ventilation which happens due to buoyancy action in the solar chimney also cleanses the air in the vicinity. Some researchers have tried integrating the concept of solar chimney in the rooms with the help of simulation from computational methods and found that the rooms get cleaner air and the temperature of the room also stays lower than the temperature when no solar chimney was installed.

1.4.2. CHALLENGES IN SCPP

One of the most interrupting challenges faced by researchers in this SCPP is about its overall efficiency which is quite low. Studies show that the efficiency of the solar chimney is linked with the height of the chimney, turbine efficiency and the collector temperature but the chimney height plays the most important role in determining the performance of SCPP. While a good efficiency of solar chimney can be achieved when the height of the chimney tower goes beyond 1000 m, which is impractical to construct a chimney of such height.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

The present study surveys the literature consists of articles, journals and other scholar works from more than last 20 years. The literature survey will provide an insight knowledge about the findings, the mathematical models and simulation related work done till now with the brief about the research work carried out by the respective researchers.

2.2. LITERATURE REVIEW

Pritam Das et. al [4] did a study by varying the diverging angle of the chimney in SCPP and found that it affects the performance of the plant in such a way that the when the angle got increased to two degrees, the velocity at the turbine location increased up to 59%. The exergy also increased by around 57% when the angle of divergence was changed. Alibakhsh Kasaeian et. al [5] adopted the computational method to check the performance of the SCPP while changing the geometrical aspects of turbine blades and validate it with the experimental data from the Manzanares plant. The study found the relation between the flow rate of mass in the chimney and rotational speed of the turbine. These parameters contributed to more torque and power of the turbine.

Jing Kong et. al [6] took the CFD approach to determine the range of optimum angle of inclination of building's rooftops. The 2-D simulation gave the results in favour of angles from 45 degrees upto the 60 degrees as the confident range of inclination angles. Erdem Cuce et. al [7] did the case study of the solar chimney plant by the computational approach to check the pressure, velocity and temperature of the air throughout the process and finally validated the results with the experimental values from the Spain plant.

Atit Koonsrisuk et. al [8] chose to validate the results by choosing some theoretical parameters. Functions are the output power and efficiency of the SCPP for creating a recommended model at the end of the study. Hussain H. Al-Kayiem et al. [9] also studied the roof top application of solar chimney in Malaysia with the help of MATLAB and found the increment in wind speed leads to the reduction of performance of the SCPP by one-fourth value, even if the model was analysed for a higher solar intensity value.

C.B. Maia et. al [10] decided to look into the exergy analysis of the solar chimney power plant at different stagnation states of temperature. The results showed the losses in exergy were significantly lesser for the lower stagnation temperature and with higher efficiency too. The study also focused on the rate of air flow inside chimney and how it's affecting the losses in energy.

Pritam Das et. al [11] formulated correlations to understand the varying nature of solar chimney's geometrical parameters along with its performance, velocity of air, efficiency and output power. The findings indicated enhancement in power and efficiency when the height of the chimney tower goes upto eight metre. The exergic efficiency of the SCPP was analysed while working with the mentioned parameters.

A. Azizia et. al [12] conducted a case study in Algeria using the computational fluid dynamics methodology to investigate a small scale SCPP and later validate it with the experimental findings. Their study concluded that the adopted methodology in their research work showed 29 kW more power in SCPP in Ouargla. Ehsan Gholamalizadeh et. al [13] investigated the working of SCPP with the CFD method under the turbine loaded condition and another one without it. Their work showed results which were in line with the earlier findings from the Manzanares plant.

Atit Koonsrisuk et. al [14] proposed a dimensional analysis method to measure output power. The adopted mathematical modelling of the plant included all parts of the SCPP along with the rotating part of turbine. It was found that nearly 85 percent of the available pressure from air is getting utilised by the turbine. H. Semai & A. Bouhdjar [15] studied the effects of geometrical conditions on the solar chimney power plant and also focused on observing the working and performance of SCPP past the sunny hours till the sunrise. The proposed effective ideas on design modifications of the storage layer to improve efficiency of the plant.

Siyang Hu et. al [16] studied the power output, velocity of air, mass flow rate of air under the modification of geometry by providing guide walls on chimney. They found the increment in power output by 30 percent in uniform circular cross-section of chimney and nearly 6 percent higher in diverging cross-section of chimney.

Penghua Guo et. al [17] studied the effect of pressure ratio at turbine section in order to improve the overall efficiency of cycle. The paper showed the usually expected results derived from the involvement of incident solar energy and the atmospheric temperature. The most suitable pressure ratio came out to be around 0.89-0.95. The analysis was done using the numerical simulation.

E.P. Sakonidou et. al [18] showed validating results from its CFD model with the experimental findings after analysing the solar chimney tower under different slopes and how it's affecting the performance of solar chimney with the other geographical parameters. Jing-yin Li et. al [19] determined a theoretical model to understand the effects of collector diameter and height of chimney from ground level. In the study, the theoretical results were in agreement with the experimental data. The height of chimney played a major role in determining efficiency of the system while the collector diameter had its limitation for maximized output power.

Hermann F. Fasel et. al [20] performed the computational fluid dynamics on the model of SCPP and found separation in flow near the chimney entry path. The simulations were time based and the flow inside the chimney was with turbulence action. Jianlan Li et. al [21] analysed the optimal parameters related to the power generation in unsteady state of study. The relation of the storage layer located at the ground had little impact over the designing conditions. Different correlations were formed involving height of collector, quality of output power and diameter of collector.

Arash Zandian et. al [22] used the steam-based Rankine cycle in Iran and found an increment of thermal efficiency upto 0.36 percent and included the idea of solar chimney use to extract dry heat from cooling tower. Guoliang Xu et. al [23] showed in their numerical methodology how most of the loss of energies is happening through collector material and lower flow rate of air will eventually help in keeping energy losses lesser. The mathematical modelling of the system was considered as the determining factor of such factors.

Sandeep et. al [24] studied the performance of the SCPP by the computational study. The radius of collector and height of chimney were not changed in any model, rather the increasing taper angles were provided to the chimney and by setting variations in inlet and outlet dimensions, the efficiency of the SCPP and its overall output power potential was analysed. M. Rafiuddin Ahmed et. al [25] proposed establishment of SCPP in countries near the Pacific region, mainly the islands in that region. He simulated almost half the chimney size of Manzanares plant's chimney height and analysed the characteristics involved in improving the system's performance to build SCPP for such lower density populated Pacific regions.

Roozbeh Sangi et. al [26] kept the primary focus on carrying out the simulation based on numerical methods and employ the continuity, energy and other important equations to validate the results with the experimental findings of the Manzanares plant. Siyang Hu et. al [27] worked on the numerical analysis part of the solar chimney power plant and validate it with the CFD results available from other researchers. The study concluded that the divergence design of chimney towers is superior to the normally proposed cylindrical design of chimneys.

Nadia Saifia et. al [28] used the computational fluid dynamics techniques to analyse the flow rate of air at outlet while varying the slope of the chimney with respect to the collector. The incident solar energy effects the outlet temperature as well as the flow rate at chimney's exit. The suitable angle of inclination was found to be around 45 degrees. Penghua Guo et. al [29] found the use of a fan as an alternative to the turbine for experimental investigation gave satisfactory results and quite feasible too rather than using the actual turbine for a model experimentation. The role of zenith angle and other parameters like sunshine hours and cost approximation were necessary to conduct before going for the experimental investigation.

Fei Cao et. al [30] analysed the different inclinations in solar chimney with the usual design of Manzanares plant to understand the effective heat transfer phenomenon in those models of study in China. The findings gave the insights of a better performance coming in larger collector diameter during winter days and the same larger diameter of collector provided unfavourable results during the summer days. S.V. Panse et. al [31] showed how using an inclination angle in chimney can also help to integrate the effects of wind in enhancing the power of solar chimney plant. The study also focused on analysis of how the energy generating inside the plant is getting distributed in different areas.

Ahmed Ayadi et. al [32] performed an experimental investigation in Tunisia and validated it with computational results. In the study, effects from operating parameters were observed, especially the collect height from the ground. The results proved how a smaller height of collector canopy can enhance the output power from the solar chimney power plant.

Alibakhsh Kasaeian et. al [33] used the CFD approach in three dimensional to study the simulation of Manzanares based SCPP with more than 10 different model which included the profile of the turbine located at chimney base. With no change in quantity of blades on turbine, and increased RPM of turbine, more power generation was noted. Moreover, with increased collector diameter and height of chimney, the output power found a significant increment. Duen-Sheng Lee et. al [34] did the study to check if the thermal results from solar chimney power plant makes it reliable source to run an organic Rankine cycle. It was found that the collection of heat made sure that it was providing electricity of 10-13 kWh/ day.

María José Suárez-López et. al [35] focused on obtaining the performance of solar chimney used as a natural ventilator by using the 3D simulation in computational method. The operating parameters were evaluated at the inlet and outlet of the chimney and validated with the existing experimental values in literature. The study provided an insight of a lower efficiency when it comes to ventilation aided mechanism of solar chimney and further research is required to enhance the performance of such system. Atit Koonsrisuk [36] compared the workings of early design of usual solar chimney with a tilted solar chimney. The comparative analysis yielded results in favour of the tilted geometry of chimney in some conditions. It was found a better option with enhanced thermal performance of the system.

M. Aligholamia et. al [37] sought to found suitable values of geometrical as well operating parameters in order to enhance the thermal analysis of solar chimney power plant. Around 10 different three-dimensional models were experimented to find a reduction in costs associated with computational work. The water repellent property at the wall provided no slip condition and rather an improvement of 10 percent of the performance in SCPP. Fei Cao et. al [38] provided and establishment of mathematical models to determine the performance of two-chimneys. It was found that the two-chimney system roughly gives 1.5 times power output than the normal design of solar chimney as well as the more numerical values of velocities in different sections of the chimney. The yearly power productions were estimated around 4.7 MW from such new design of proposed two-chimney system.

Xinping Zhou et. al [39] proposed a system which involves the integration of waste heat coupled with SCPP. The operating parameters were evaluated at respective points to note the actual enhance in values when flux from waste heat was used upto the 1-3 GW, this further showed an exceptionally great power generation by nearly 120 percent. Suad Hassan Danook et. al [40] performed the three-dimensional computational method for Kirkuk city and found the most power production was observed in the month of July with high air velocity of around 18 m/s at the turbine location. The January month yielded very less velocity of around 8 m/s due to the nature of winter weather having less solar radiation. The monthly average of power generation was found nearly 14.4 MWh when working in effective weather conditions.

Erdem Cuce et. al [41] studied the effect of solar chimney height in power generation through CFD method. The computational work had the findings of the variation of power from 50 kW to nearly 130 kW when the chimney height was increased from the 0.2 km to 0.5 km. The results were fairly synchronising with the early experimental findings. Hardi A. Muhammed et. al [42] focused on optimizing the geometrical aspects with the computational methods and the study targeted more than 10 groups each for the height of chimney and collector with more than 100 cases in both parts of the SCPP. The aim of the study to design an effective and accurate model for decisions was formulated.

Siavash Haghighat et. al [43] integrated the photovoltaic solar panels with the solar chimney. The installation of those PV panels at different location beneath the canopy of collector were setup with different width of panels. The results in the study found due to cooling action of air flow below collector, the average temperature of solar PV panels decreased by a significant margin of 4 to 6 degree Celsius and a small reduction in air flow velocity. Omer Khalil Ahmeda et. al [44] used a case study in Iraq to see the performance of SCPP with the solar photovoltaic modules in different orientations and design. The system with glass as collector and photovoltaic panel as an energy storage showed more collection of thermal heat and hence provided higher velocity to the system as compared to another system where plywood was used as an energy storage medium with PV panel being used in place of glass as collector.

J. Xaman et. al [45] used time dependent numerical analysis with three different types of materials of absorbers with assumption of losses of energy to the environment on the hottest day of Spain. It was observed that phase change material underwent the phase change into liquid state when oriented towards the western direction. Fei Cao et. al [46] initiated a comparison between the inclined solar chimney and the usual design of solar chimney to study the power generation which was observed under conditions of maximised solar incident angle and the angle from which most power can be extracted. In the findings, it was concluded that the inclined solar chimney power plant generated more continuous supply of power with the best solar incident angle, more power through the identified angle for maximised power generation in colder seasons of the year.

Yangyang Xu et. al [47] studied the divergence nature of solar chimney in SCPP and proposed the relation of the plant's performance based on the ratio of area at chimney's exit and at the entrance of chimney. The study concluded that the optimum ratio was in between 8 to 9 for the maximised power output. Erdem Cuce et. al [48] studied the impact of ratio of areas too in both convergence and divergence cross section of solar chimney by varying the ratio upto ten. The adopted computational methodology revealed that the existing Manzanares plant's power generation capability can be improved by 100 kW with the suitable areas' ratio from 4 to 6.

Jing Kong et. al [49] pushed the efforts towards determining the suitable slope of inclination in natural ventilation aided roof top chimney for cities in Australia and concluded that the best suitable angles are in between the 45 degrees to 60 degrees. Ajeet Pratap Singh et. al [50] investigated the cool down of solar PV modules placed under the collector and found the significant drop in the temperature of modules by 9-11 degree Celsius. Lu Zuo et. al [51] involved the use of axially based impeller used in hydraulic application and found an increment of about 30 percent higher power generation with the new design than the existing results from Manzanares plant. T. Z. Ming et. al [52] employed the understanding of ideal Brayton cycle and actual cycle to analyse the thermodynamic nature of the working of solar chimney power plant.

The results showed efficiency of nearly 1 percent in ideal case while 0.2-0.4 percent in actual cycle of working.

S. K. Das et. al [53] did an early-stage study in late 1980s to see the application of solar chimney for rural side application. The investigation resulted in quicker drying of paddy crops and showed that it can save 6 to 8 hours of time when compared to drying of crops in open area as done conventionally in fields. Xinping Zhou et. al [54] did the research work in Tibet region and used the mathematical analysis to come to a conclusion that the establishment of SCPP in Tibet region can actually produce nearly two times more power than any other such establishment anywhere else on same geographic latitude. The amount of power generation will be good enough for small local activities and development happening in the region.

Sajjan Raj Keshari et. al [55] studied the slope of collector with the chimney tower and worked on to analyse the operating parameters to extract maximum amount of work and output by changing the slope. Th work concluded the most suitable inclined angle to be around 5 to 7 degrees. K.S. Ong et. al [56] carried out an experiment with two meters high solar chimney on roof-top and found the achieved radiation incident of around 600-660 kW with velocity of air being nearly 0.20 m/s to 0.40 m/s. T.P. Fluri et. al [57] investigated the working with impeller design such that the study involved in testing blades with and without guide angles. It was found that the impeller without the blade angle performed very low in terms of power and output velocity.

P.J. Cottam et. al [58] carried out the work regarding the design of collector profile to improve the efficiency of the SCPP. The research work proposed a new design of the collector's profile and found it has to be designed in a way to facilitate higher kinetic energy of flow at chimney base. Weibing Li et. al [59] focused the work more on economic aspects of building a solar chimney power plant and evaluating the commercial cost of the produced energy to be consumed by public with existing electricity cost in a localised region of China. The results obtained proved that the cost of power from solar chimney will be higher in the beginning phase but it will go down under the subsequent upcoming stages of power production.

E. Bilgen et. al [60] evaluated the performance of SCPP in three different northern American regions to see the efficiency and power output of SCPP at higher elevations.

The obtained results showed the output power of SCPP in proposed locations was nearly 80 to 90 percent of the same SCPP in other warmer regions.

Xinping Zhou et. al [61] proposed a suitable height for maximum power generation for the Spain plant by using theoretical analysis. The findings revealed the maximum power generation can go upto 100kW with height of chimney of nearly 600 m. Ming Tingzhena et. al [62] validated the Manzanares plant's experimental results with its simulation based on numerical analysis with three blades on impeller. The numerical work further proposed five blades profile for the SCPP and found the power generated to be around 9-10.2 MW with efficiency of impeller around 0.5.

Chiemeka Onyeka et. al [63] studied the working performance of SCPP in Cyprus region by validating the parametric results from the study with the Spain plant and found that the establishment of such system can fulfil the demands of nearly 22 thousand people with a fair feasibility in cost matrix. Amitabha Satpathi et. al [64] provided an idea for the impact of integration of heat engine with working medium as carbon dioxide to improve the efficiency of the SCPP. The weaker thermophysical properties of carbon dioxide made it clear that the actual experiment on a prototype will reveal the results in more precise way.

Hakim Kebabsa et. al [65] carried out the work in the field of understanding the nature of performance of SCPP with inclined and angled design of solar chimney and later validate it with experimental work. It was found that the most suitable inclination would be around 9 degrees for maximum power generation and around 16 percent more power as compared to the design with no inclination. Cristiana Brasil Maia et. al [66] modelled the solar chimney system in Brazil to help dry up the fruits in a low scale prototype to see the effects. It was found that the fruits dried up faster when used with the system's energy. The exergetic efficiency increased significantly upto 26-28 percent without any load condition.

Vivek Praveen et. al [67] presented a numerical investigation in comparing two different designs of SCPP. One design with a fillet of certain slope = 1 and another one with no slope. The numerical working showed the design with a fillet has greater efficiency, power output and thermal efficiency too. Mukundjee Pandey et. al [68] worked in computational fluid dynamics to utilise the low waste heat recovery to achieve a good working condition during night and days with more clouded sky and found it a good fit for such timely conditions.

E. Gholamalizadeh et. al [69] proposed a numerical model to evaluate the parameters of SCPP in Iran. The aim of study was to give attention to the elevation and other geographical parameters and their effect on determining the efficiency of solar chimney power plant. The numerical approach stated that the collector radius is the most important parameter in improving the efficiency. Ammar Mebarki et. al [70] performed their computational analysis by lowering the actual design by half the factor with the incident solar energy in more than 25 scenarios. The solar irradiation was kept constant and it gave different results under different scenarios.

A. Bouchair et. al [71] developed a theoretical study in early 1980s to determine how azimuth is playing a role in solar radiation being collected. The study provided the insight of the direction's influence on performance of solar chimney and concluded that for the best ventilation condition, the chimney is supposed to be in western direction of the room. H. Hoseinia et. al [72] evaluated mathematically the influence of the collector's orientation and the nature of its angle near the chimney. The results were used to conclude that the divergence shape of the collector provides greater generation of power by more than 10 percent and slightly lesser temperature at chimney's exit.

Yaswanthkumar Amudam et. al [73] included a three-dimensional study in work by comparing a SCPP model with absorber layer and another one without the absorber layer. The results showed the model without absorber layer performed better as it was continuously providing heat flux while the model with the absorber layer provided less efficiency and power output.

2.3. RESEARCH GAPS IDENTIFIED

There exists wider scope of research on SCPP, specially to find the way to increase the flow speed of air near the turbine. Most researches are coming from Mediterranean regions, dry regions, there still exists the possibility and scope to understand the behaviour of SCPP under humid conditions and how can the power generation be enhanced in such regions with higher humid climatic conditions. While the design part of the SCPP is focusing more on the canopy and inclination angle, there still exists gaps to identify more about how the base of the plant can be designed to provide a turbulence in the air flow region. For which the surface geometry of base becomes important. While the limitation of SCPP is the installation height of chimney tower, more ways are yet to be discussed in which the heat transfer mechanism can be enhanced to yield better efficiency.

Apart from studying geometric parameters of solar chimney, the materials used for the parts is focused less and given less attention in past years. The SCPP can perform much better when used in integration with another mechanisms. Finding more such mechanisms or systems may open more doors for SCPP.

CHAPTER 3: MODELLING AND METHODOLOGY

3.1. DESIGNING PARAMETERS

The designing parameters of the SCPP involve the 3-dimensional modelling in the SolidWorks software with below dimensions taken from the Manzanares plant.

Table 3. Specifications of the SCPP design

Parts of the Solar Chimney plant	Dimensions
Collector mean diameter	122.02 metres
Total height of the chimney	200.01 metres
Diameter of chimney	10.18 metres
Turbine radius	4.28 metres
Height of the base	9.08 metres

After designing the 3D model of solar chimney. Further, 3D model of turbine blade profile FX-W--151 was designed using the parameters available [74].

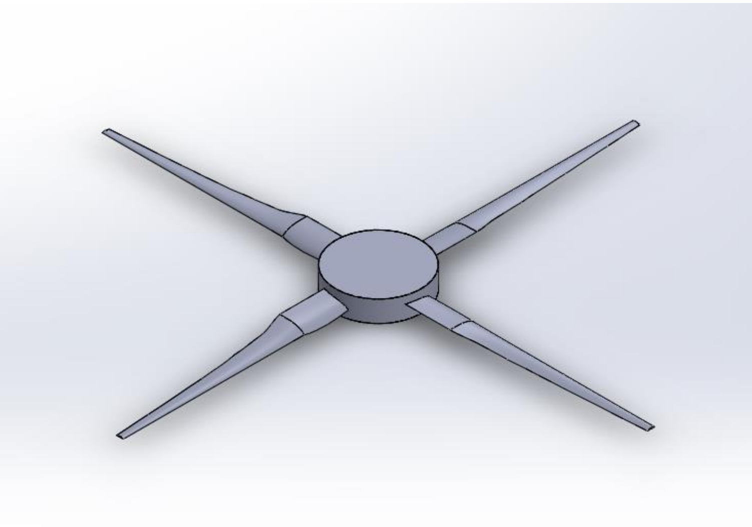

Fig.2. Turbine impeller profile – FX-W-151

After the designing of the turbine profile, all parts namely collector, turbine, chimney tower were assembled and the final model was ready to go under the analysis after proper mating of axis and faces.

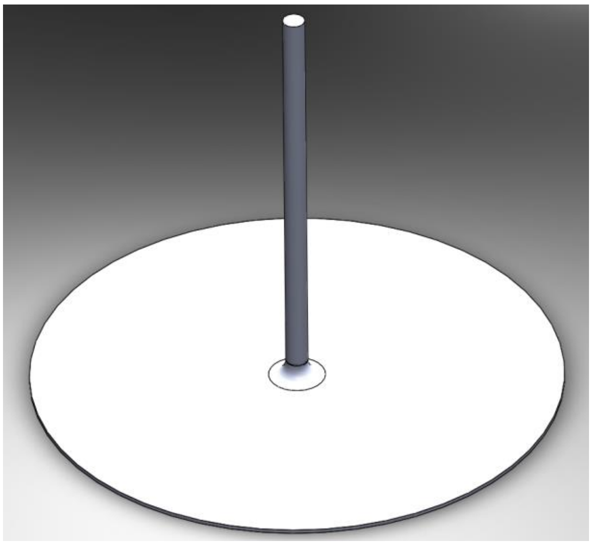

Fig.3. Final assembly of solar chimney system

The final assembly was exported in the “Parasolid” form to the ANSYS - Fluent (2022 R1). Apart from this 3D full view of the actual plant’s design. There was another 3D designing of only revolution of 15 degrees of the original design. This was designed in DesignModeler to do analysis on microscale with operating parameters.

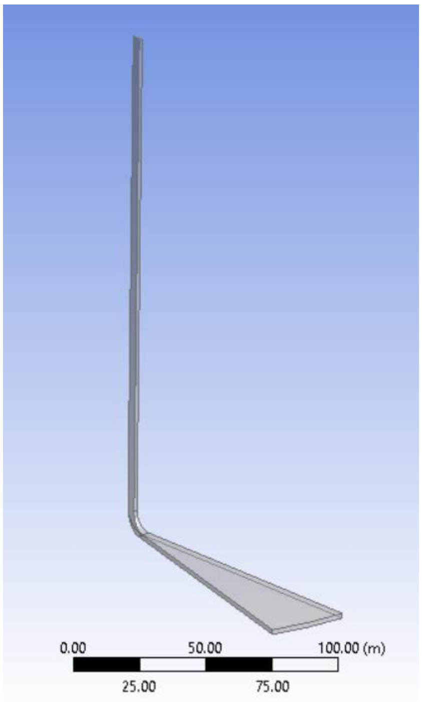

Fig.4. The 15 degrees revolved 3D model of the original geometry

3.2. MATERIALS FOR THE COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

Materials used for each part of the analysis are given in Table 3 below.

Table 4. Description of materials used in the CFD analysis

Part of SCPP design	Material used for analysis
Ground	Solid rock gravel
Collector	Normal glass
Chimney	Aluminium (Al)
Base	Aluminium

3.3. THERMO-PHYSICAL PROPERTIES OF MATERIALS USED IN SIMULATION

The thermophysical properties of above-mentioned materials is available in Table 4.

Table 5. Thermophysical properties of the materials used

Properties	**Materials**		
	Aluminium	**Rock Gravel**	**Normal Glass**
Thermal conductivity (W/m-K)	202.0	1.82	1.4
Density (kg/m^3)	2720.0	2152	2490
Specific heat (J/kg-K)	880	704	740
Absorption Coeff.	0	0.89	0.04
Refractive Index	1	1	1.52
Material nature	Opaque	Opaque	Semi-transparent
Emissivity	1	0.89	0.2

The thermophysical properties were taken from the understanding of how these values will be behaving when under the ambient temperature and pressure conditions.

3.4. OPERATING CONDITIONS OF THE SURROUNDINGS

The operating conditions of the surrounding air as working fluid are in given below.

Table 6. Operating conditions of Air and other general values

Conditions	Values
Temperature	300 K
Pressure	101.326 kPa
Viscosity	1.8×10^{-5}
Gravity	9.82 m/s^2
Density	1.2058
Gas constant (Air)	0.2867 kJ/kg
Heat capacity (Air)	1005.9 J/kg-K
Stefan Boltzmann constant	5.66×10^{-8} W/m^2-K^4

Apart from the above-mentioned values, the CFD simulation will be conducted to first validate the model's accuracy and then the same model will be used to analyse the results for Indian locations such as Mahendragiri, Kutch, Ladakh. The choice of locations has to do with the analysis of India's potential performance in solar chimney system in places from all directions and later compare the results with each other.

The day and time for the analysis are chosen to be 21st June and at 13:00 hrs, so as to get the results from one of the hottest days in year. The geographical coordinates of the mentioned locations are used to get the direction of sun on the day and the amount of solar irradiation, diffused radiation and the reflected radiation which are calculated from the solar-calculator in ANSYS.

The latitude and the longitudes of the places taken into the study are provided in Table 6.

Table 7. Geographical information of the Indian cities used for the study

Name of cities	Latitude	Longitude
Ladakh, UT	34.2173 ° N	77.5297 ° E
Mahendragiri, Odisha	18.9761 º N	84.3701º E
Kutch, Gujarat	23.7319 ° N	69.8218 º E

The above cities were simulated under different values of solar irradiation at 600 W/m^2, 800 W/m^2 and 1000 W/m^2.

3.5. GENERAL EQUATIONS, ASSUMPTIONS AND MODELS

The CFD analysis has been kept under the steady state analysis. By understanding the effects driving the air flow in this simulation and the varying density of air because of change of temperature inside the collector and the chimney, Boussinesq approximation has been absorbed into the study. It also takes the buoyancy phenomenon. Tracing the solar irradiation direction is one of the necessary requirements of current model to produce accurate results that is why Discrete Ordinate mechanism finds its application here. The chimney walls are assumed to be thermally insulated to avoid leakages of energy and heat. Along with the k-epsilon, the RNG method has been applied to ensure the turbulence is taken into account upto a good limit to ensure a good flow under chimney and other parts. The RRE is one of the method used as polynomial function to speed up the convergence of iterations. The governing equations used are-

Energy equation –

$$\frac{\partial(\rho kT)}{\partial t} + \frac{\partial(\rho kuT)}{\partial x} + \frac{\partial(\rho kvT)}{\partial y} + \frac{\partial(\rho kwT)}{\partial t} = \varsigma\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

Continuity equation –

$$\frac{\partial(\rho v_j)}{\partial y_j} = 0$$

RNG k-ε equation-

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + W_k - \rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right] + D_{1k}\frac{\varepsilon}{k}W_k - W_{2\varepsilon}^{*}\,\rho\frac{\varepsilon^2}{k}$$

CHAPTER 4: RESULTS & DISCUSSIONS

Firstly, to test the validation of the CFD model used in this study, the results under almost similar working conditions were simulated in ANSYS CFD and the results were plotted with the results from the Erdem [7] with irradiation of 1000 W/m^2.

Table 8. Comparison of result values of maximum velocity achieved in this study and study by Erdem [7].

Solar Irradiation (W/m^2) =1000	Erdem [7]	Present Study	Variation
Velocity	14.24 m/s	13.82 m/s	**-2.94 %**
Pressure at the turbine	-76.79 Pa	-76.1 Pa	**- 0.8 %**
Temperature difference from the ambient temp.	18.95 K	19.12 K	**+ 0.89 %**

The results above show nearly 3% lesser values of velocities are obtained. The difference may have been due to the difference in geometry of designs in both studies. While the present study has a design near base where the cross-sectional area increases after the air enters from inlet while in geometry used by Erdem in the study didn't have such increasing passage which may have contributed in loss of some kinetic energy.

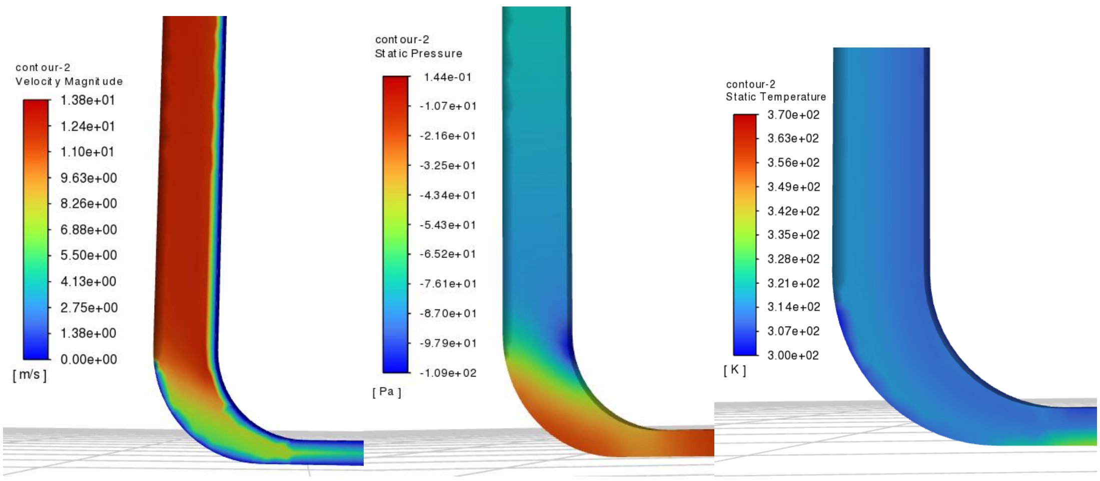

Fig. 5. Values of velocity, static pressure and temperature obtained in the present study.

From the above results, it’s quite evident that the CFD model used in present study is in agreement with findings of other research work in CFD modelling of the solar chimney. With the validation, the results for Indian locations were simulated to see if how much these cities would work if the SCPP is built in the respective places.

4.1. Ladakh, UT

The following results are derived with the geographical values of Ladakh, UT. The ambient temperature of 300K.

Table 9. The output results from the CFD model in Ladakh, UT.

Solar Irradiation (W/m^2)	Pressure (Pa)	Velocity (m/s)	Temperature (K)
600	-73.82	11.37	348.26
800	-92.78	12.71	359.84
1000	-108.74	13.75	370.47

4.2. Mahendragiri, Odisha

When it comes to Mahendragiri, the ambient temperature is taken as 303 K to get more closer results to the realistic weather during the day of which we have setup the solar tracing.

Table 10. The output results from the CFD model in Mahendragiri, Odisha.

Solar Irradiation (W/m^2)	Pressure (Pa)	Velocity (m/s)	Temperature (K)
600	-72.90	11.30	350.66
800	-91.78	12.65	362.11
1000	-107.56	13.75	370.49

4.3. Kutch, Gujarat

For Kutch too, the ambient temperature is taken as 310 K.

Table 11. The output results from the CFD model in Kutch, Gujarat.

Solar Irradiation (W/m^2)	Pressure (Pa)	Velocity (m/s)	Temperature (K)
600	-71.65	11.28	356.25
800	-88.60	12.51	367.45
1000	-104.05	13.53	377.79

After finding the simulation results, its necessary to see how these places in India compare with each under the defined solar irradiation being incident on their collector areas. The comparison among four cities will give better insight of the capability and solar energy potential of the location.

4.4. PRESSURE COMPARISON

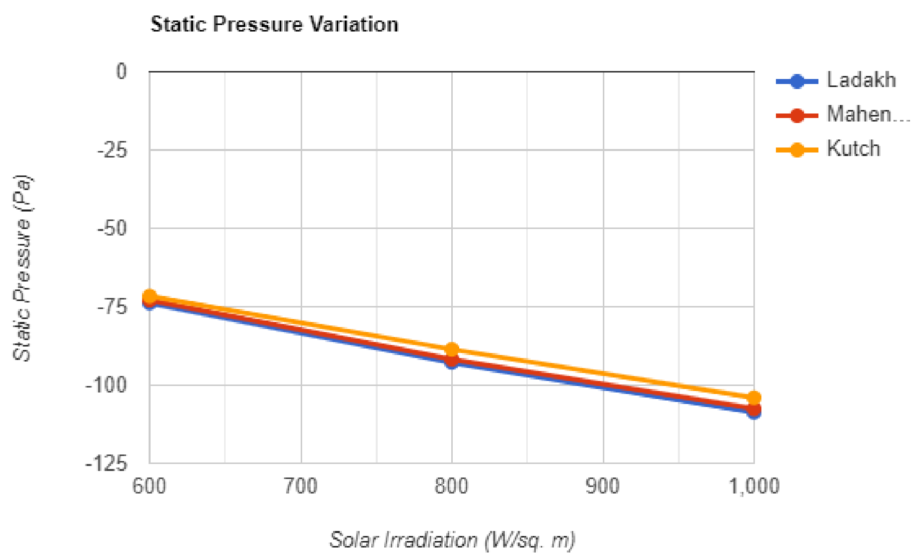

Fig. 6. Static pressure variation with the Solar Irradiation for all three cities

4.5. VELOCITY COMPARISON

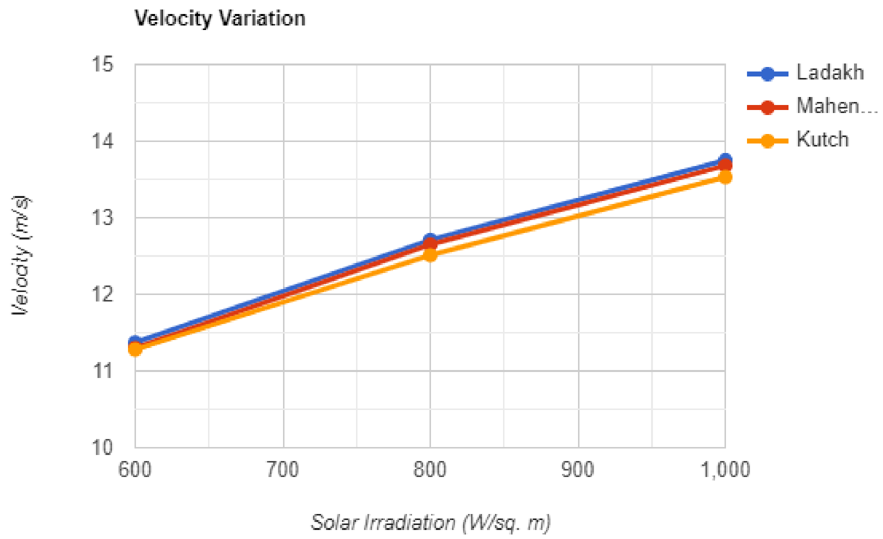

Fig.7. Velocity Variation of all three cities with varying solar irradiation

4.6. TEMPERATURE VARIATION

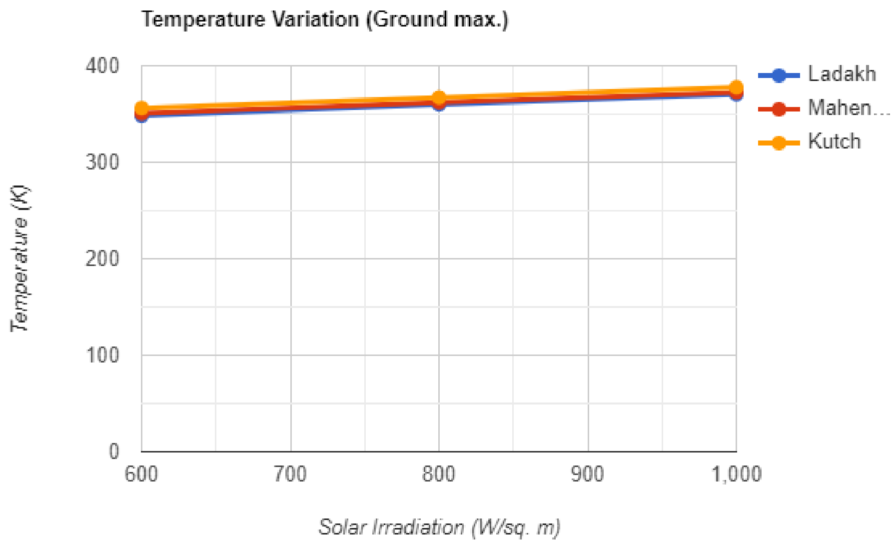

Fig. 8. Variation of temperature of ground surface in all places

CONCLUSION

The present study shows an impressive potential of Ladakh for establishment of a small-scale pilot plant with maximum velocity of 13.75 m/s achieved at solar irradiation of 1000 W/m^2. Mahendragiri has the benefit of lying in the tropical area of India and hence, it showed a good performance too. The Kutch region of Gujarat has significantly higher ground temperature than other two cities. The three cities showed a good performance and may be better than many other places where the research work about SCPP is already in working mode.

The study shows a promising effect toa degree that upon being integrated with other systems, the mechanism would work better. There is a need of more work needed in India to be done in the SCPP for a better, reliable and affordable electricity.

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