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Direct steam generation for process heat applications in compound parabolic collector (CPC)

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Abstract

In recent years, CPC (Compound Parabolic Collector) is gaining its acceptance for temperature range higher than non-concentrating stationery solar collectors like flat plate collectors but lower end of temperature range of concentrating solar collectors like PTC (parabolic trough concentrators). Generally, pressurized hot water or thermal oil is used as a working fluid in the CPC. The elimination of solar tracking in CPC provides flexibility for installation and lower price point compared to other concentrating technologies with tracking.

Steam is one of the universally accepted working fluid for process heat applications due to availability, non-toxic and high heat carrying capacity. Many industrial sectors such as food and beverages, textile, chemical processes etc utilize steam as a working fluid for process heat applications. Direct steam generation as a working fluid through a CPC has various operational, integration and cost advantages. The use of CPC for direct steam generation at saturation steam temperature range 105-145 °C (equivalent saturation pressure 0.5-3 bar (g)) can cater for low temperature process heat demand. Solar radiation intensity changes with the time of the day leading to change in heat flux for steam generation. There are challenges for handling two phase flow (steam generation) in 'U' shaped metal tubes due to pressure drop, flow instabilities and control of steam dryness fraction under varying solar heat flux.

The focus of the present research work is to analyze a CPC system for direct steam generation. This paper discusses an experimental setup and challenges for direct steam generation. The experimental measurements will be focused on behavior of the thermal flow pattern inside the inclined metal tube at various heat flux conditions throughout the day, measurement of local heat transfer coefficients and corresponding vapor quality. Experimental data analysis and understanding will be useful to develop direct steam generation engineering schemes and its integration approach with various end-use applications.

Keywords: *CPC, process heat, process steam, two phase flow*

1. Introduction

The fossil fuel is used for electricity generation and process heat applications. Considering adverse effects of fossil fuels such as air pollution and global warming, it is important to promote renewable energy technologies especially in industries (Garud and Purohit 2013). The process heat requirement in an industry typically varies from 80 ºC to 250 ºC. Steam is widely accepted working fluid to cater the temperature range of 80-180 ºC, thermal oil is a preferred choice above 180 °C.

Solar thermal technologies are of concentrating and non-concentrating type. Traditionally, the non-concentrating technologies are used for end-use temperatures less than 80 ºC, and the concentrating technologies are used for medium end-use temperature applications. The concentrating technologies track the Sun and reflect its radiation to the focal point of a concentrator. Medium temperature concentrating

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technologies provide temperatures in the range 80–400°C and are used mainly for process heat applications (Sukhatme & Nayak, 2008).

The major considerations for adoption of solar thermal technologies for process heat applications are existing working fluid, end-use temperature requirement, shadow free space available for solar installation and cost of solar thermal technology. The solar thermal technology providers are innovating to brake the conventional barriers for working fluid limitation, maximize system efficiency (reduce area and improve ability to cater higher temperature) and minimize cost of solar thermal system.

The CPC (Compound Parabolic Concentrator) technology is in the market from more than 25 years, it is combination of a stationery (evacuated tube) and a concentrating technology (reflector) with no tracking requirement, this also known as a non-imaging technology. The elimination of solar tracking provides ample flexibility for choice of installation areas and simple operation. Generally, single phase working fluids like pressurized hot water or thermal oil is used in the CPC for the temperature range of 80-130 °C. The use of CPC operating with single phase working fluid in steam system requires additional heat exchange devices and higher solar system operating temperature leading to increased capital cost and reduced thermal performance (due to high operating temperature).

This paper discusses the considerations and approach for the direct steam generation from the CPC. An experimental setup and measurement protocol for proposed for direct steam generation is also discussed in the paper.

2. Industrial process heat and solar thermal technologies

2.1 Industrial process heat

Process heating is an essential component in the manufacture of most of the industrial products, typically, the energy used for process heating accounts for 2% to 15% of the total production cost (U.S. Department of Energy 2001).

Share of industrial heat demand for different temperature ranges based on data from 32 countries is shown in figure 1. About 30% of the total industrial heat demand is required at temperatures below 100°C and 27% at temperatures below 400°C (IEA SHC Task 33 2008).

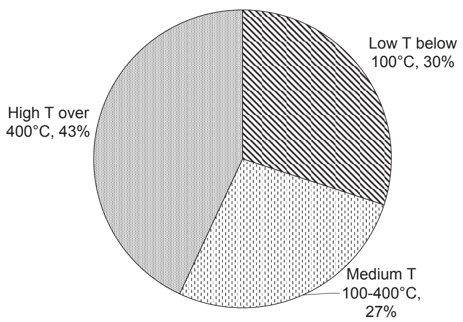


Figure 1: Share of industrial heat demand by temperature level. (IEA SHC Task 33 2008)

The majority of heat demand in industrial sectors, is at low and medium temperature. Saturated steam is generally a preferred working fluid for process heat demand below 180 °C. Steam system of a process plant has three major sections namely, generation, distribution and utilization. The steam generation is performed in a boiler (fired pressure vessel) and it is distributed using insulated steel pipes in the plant. Saturated steam has fixed pressure and temperature relationship; the desired temperature is achieved by adjusting the steam pressure. A typical steam generation, distribution and utilization system is presented in figure 2. Steam is generated at a pressure close to the boiler design pressure, even if this is higher than is needed in the plant. The steam pressure is adjusted to desired end-use temperature using pressure reducing station.

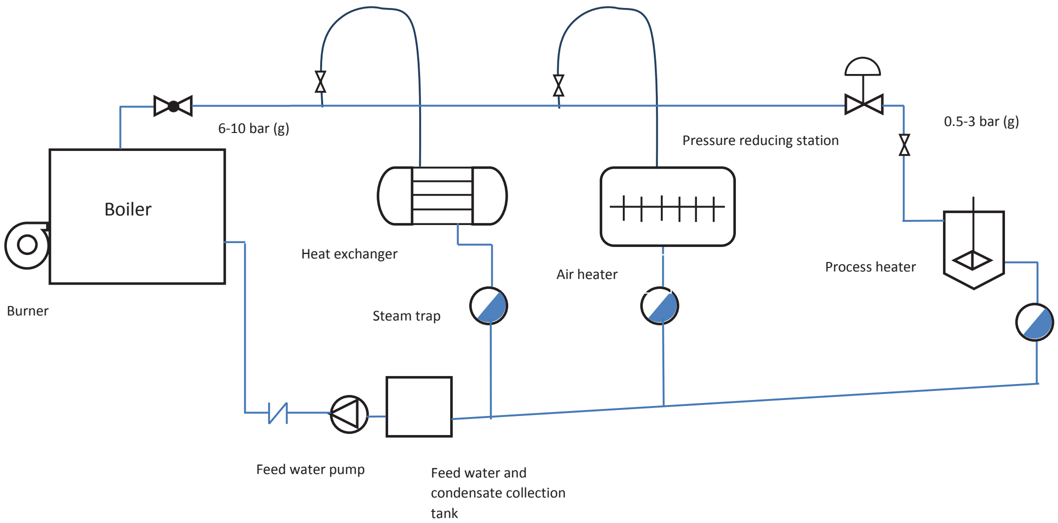


Figure 2 Typical steam system in a process plant

The key sectors utilizing industrial process heat are food (including wine and beverage), textile, metal, plastic, paper, dairy and chemical. The areas of application with the most suitable industrial processes, include cleaning, drying, evaporation and distillation, blanching, pasteurization, sterilization, cooking, curing, painting, and surface treatment. The typical temperature range for various applications is presented in table 1.

2.2 Solar thermal technologies

The popular concentrating and non-concentrating technologies for the process heat application is presented in figure 3. The temperature range for these technologies is presented in figure 4. There are different concentrating technologies suitable for different temperature ranges. There are two major types of concentrating technologies non-imaging (no tracking) and imaging (with tracking). The typical concentration ratio for non-imaging technologies is in the range of 1-10 and above this concentration ratio imaging technologies i.e. technologies with tracking are practiced (Rabl 1985).

Non-imaging concentrators have the capability of reflecting to the absorber all of the incident radiation within wide limits. The absence of tracking makes the CPC to accept incoming radiation over a relatively wide range of angles.

Imaging concentrators use tracking reflector systems to focus radiation onto a receivers (absorber) that is located at the focal point. Parabolic trough concentrators use parabolic trough reflectors to produce a linear focus on a receiver that moves with the trough as it tracks the Sun. Linear Fresnel systems use an array of smaller parallel reflectors that track individually onto a fixed linear receiver. Paraboloidal dish concentrators focus to a point focus receiver located at the focal point.

Table 1: Industrial sectors and processes with the greatest potential for solar thermal uses (Intelligent Energy, Europe 2006)

Industry	Process	Temperature ^{0}C
Dairy	Pasteurization Sterilization Drying Concentrators Boiler feed water	60-80 100-120 120-180 60-80 60-90
Tinned food	Sterilization Cooking Bleaching	110-120 60-90 60-90
Textile	Bleaching, dyeing Drying, degreasing dyeing Fixing Pressing	60-90 100-130 70-90 160-180 80-100
Paper	Cooking, drying Boiler feed water Bleaching	60-80 60-90 130-150
Chemical	Soaps Synthetic rubber Processing heat Preheating water	200-260 150-200 120-180 60-90
Meat	Washing, sterilization Cooking	60-80 90-100
Beverages	Washing, sterilization Pasteurization	60–80 60–70
Flours and by-products	Sterilization	60–80
Timber by-products	Thermo diffusion beams Drying Pre-heating water Preparation pulp	80–100 60–100 60–90 120–170
Bricks and blocks	Curing	60–140
Plastics	Preparation Distillation Separation Extension Drying Blending	120–140 140–150 200–220 140–160 180–200 120–140

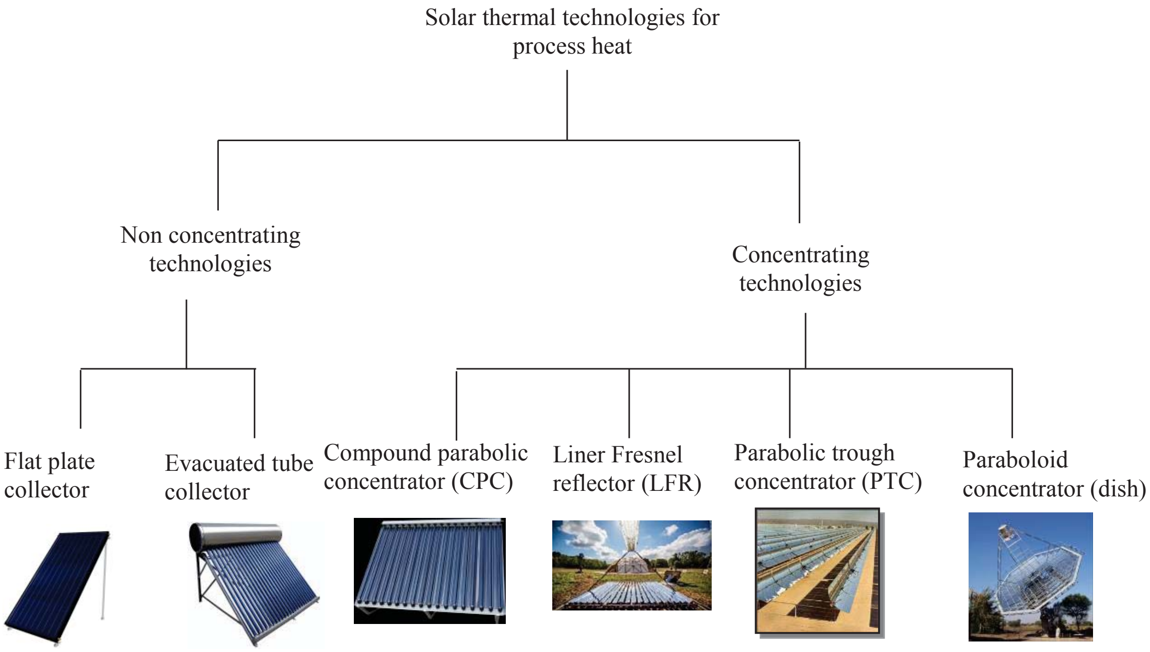


Figure 3 Popular solar thermal technologies for process heat applications

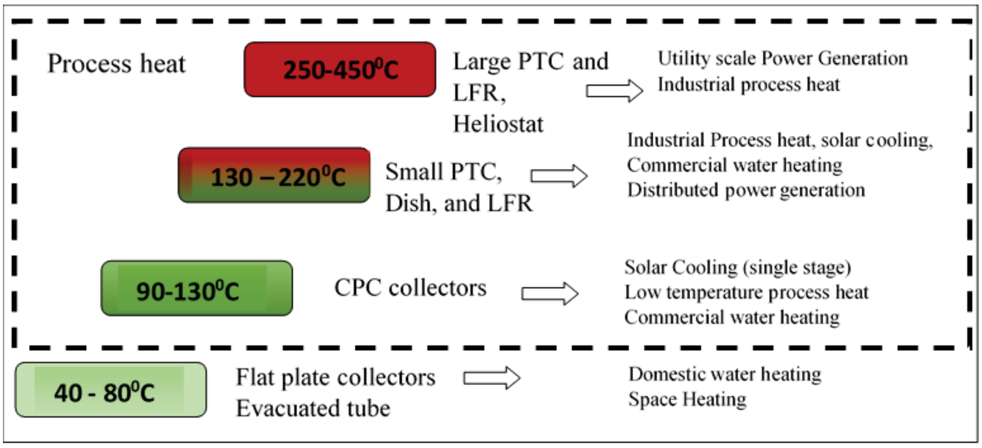


Figure 4 Solar thermal technologies and generation temperature range (ccilaportugal 2016)

It should be noted that quite often industrial processes utilize medium temperature heat in the form of steam even though for actual process lower working temperatures (below steam temperate in the range of 80-130 °C) would be sufficient. Performance of solar thermal system is better at lower operating temperature. Therefore, in order to assess correctly the feasibility of the solar thermal in an industrial process, one should look at the actual temperature needed by the process itself and not get driven by the utilization temperature of the heat carrier being used. Such an approach should be adopted to maximize overall performance of the solar thermal systems in process heat application.

Apart from temperature requirement, the other major consideration for solar thermal technology adoption is a system cost and suitability of an installation area. The CPC is non-imaging technology suitable to deliver heat at 90-130 °C temperature range at 20-40% lower system cost compared to imaging type technologies. The lower cost is mainly on account of no tracking requirement, no moving parts and simple installation structure. In addition to the system cost advantage, the CPC is flexible to install on a slanting roofs and has weight 18-22 kg/ m^2 aperture area compared to other concentrating technologies which have limitation for installation on the slanting roofs and the weight of such systems is in the range of 40- 80 kg/ m^2 aperture area

There are variety of applications like steam tracing, evaporation, boiling processes in cooking, essential oil extraction, pasteurization, sterilization etc. requires heat at 90-130 °C temperature range in the form of steam. In the process plants steam for such applications is supplied after PRS (pressure reducing station) in the pressure range of 0.5-3 bar (g) (shown in figure 2).

Generally, liner receiver systems use sensible heating working fluid either thermal oil or pressurized hot water for extracting heat from the solar thermal system. The sensible working fluid can be used for indirect steam generation using external heat exchanger and accessories. Indirect steam generation as process heat working fluid from concentrating solar system has various operational limitations and cost disadvantages captured as follows:

- Indirect steam generation requires additional steam generating system increase system cost, not very economical for small systems (below 100 m^2 aperture area)
- Lower solar thermal system performance as the sensible working fluid temperature needs to be 10 to15 °C higher than the steam generating temperature
- Continuous operation of sensible working fluid circulation pump leads extra energy cost for pumping
- Design of steam generating heat exchanger for varying sensible working fluid flow (30% -100%) on account of variation in the solar radiation during the day

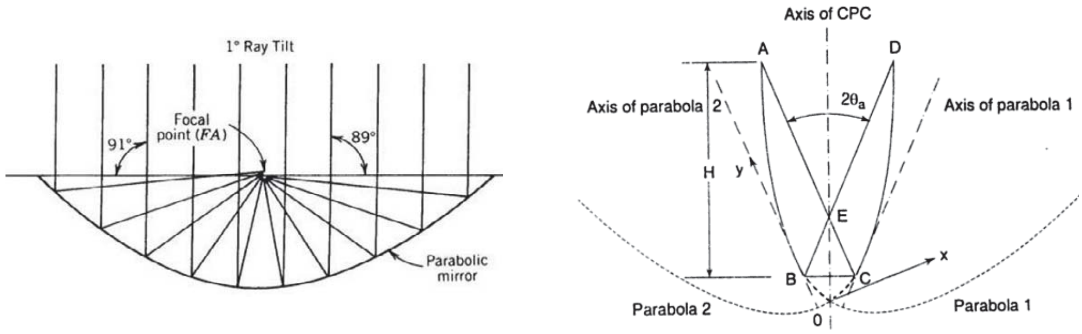
3. CPC technology

3.1 Basics of CPC

Compound Parabolic Concentrator (CPC) is a special type of solar collector fabricated in the shape of two meeting parabolas. It is a hybrid, non-imaging solar thermal system with high aperture area. The concentration ratio up to 10 can be achieved in the non-tracking mode easily (Rabl 1985). The geometry of a CPC is as shown in figure 5. It has two parabola sections AB and CD of parabola 1 and 2 respectively. AD is the aperture area with width ‘w’, while BC is the absorber area with width ‘b’. The axis is oriented in such a way that C is the focus of parabola 1 and B is the focus of parabola 2. Also the height of the collector is so chosen that tangents at A and D are parallel to the axis of the collector.

The acceptance angle of the CPC is the angle AED. It is obtained by joining the focus to the opposite aperture edge. In the CPC, reflector segments are oriented such that the focus of one segment lies at the base of the other segment which is in contact with the receiver. With this type of arrangement, the rays which falls in the central region reaches the absorber directly whereas those falling near the edges undergo certain reflections. The optical efficiency for a CPC is around 65%, which is 8% more as compared to a parabolic trough collector (Sukhatme & Nayak, 2008). The concentration ratio (CR) is given by w/b. For a concentrating collector the amount of diffused radiation that can be collected is given by 1 /CR. Thus the advantage of a CPC is that it can collect diffuse radiation delivers partial heat output during cloudy atmosphere.

CPC are generally oriented in the East – West direction with south facing aperture area (for northern hemisphere), so that the maximum sunlight is utilized. However, for application where the concentration ratio is high or the acceptance angle is less, than tracking is to be provided to ensure that sunlight falls continuously on the CPC.

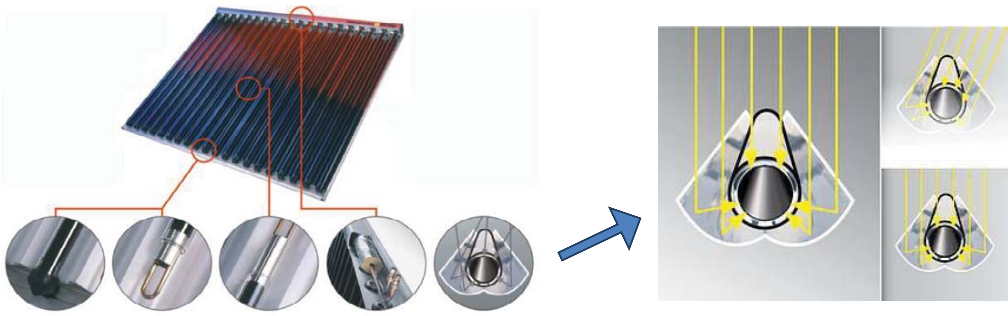


(a) (b)

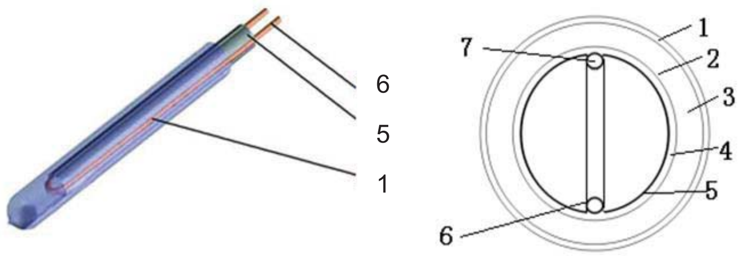
Figure 5: Construction of Compound Parabolic Concentrator (a) single parabolic mirror (b) two intersecting parabolas (Sukhatme & Nayak, 2008)

3.2 Construction of CPC

The main components of CPC technology are an evacuated tube, a compound parabolic reflector and a metal tubes (enclosed in the evacuated tubes) for transporting working fluid. The evacuated tube is a double sided selective surface coated glass tube receiver with vacuum envelop in the two glass surfaces. The evacuated tube is mounted inside the compound parabolic reflector. An 'U' shaped metal tube is enclosed in the evacuated tube, the metal tube is connected to the common headers for supply and return of working fluid. Pictorial view of CPC is as shown in figure 6.



(a)



(b)

1: Outer tube 2: Selective absorption coating 3: Vacuum gap 4: Inner tube 5: Transfer plate 6: U metal pipe 7: Working fluid

Figure 6: (a) Pictorial view of Compound Parabolic Concentrator (b) Internal 'U'tube (Linuo Ritter International 2014)

The evacuated tube receives direct solar radiation from upper surface (surface facing the sun) and receives reflected solar radiation from the bottom surface (surface facing reflector). The radiation received on the upper surface utilize both beam and diffuse component of solar radiation (global radiation) and the bottom surface utilizes only reflected beam component of solar radiation. Direct, diffuse and reflected solar radiation is received on the outer layer of a glass tube (evacuated tube); it is then passed through the vacuum, and is then absorbed upon a specialized coating on the inner layer of the glass tube. Heat is then radiated and conducted from the inner layer of the glass tube to a metal tube. Heat absorbed by the metal tube is transferred to a working fluid flowing inside the metal tube. Pressurized hot water or thermal oil is used as the working fluid to extract heat captured in the evacuated tube. The general arrangement for the sensible heating of working fluid using the CPC array is presented in figure 7. The major components of the system are CPC modules, a circulation pump, an expansion tank, a heat exchanger and piping accessories.

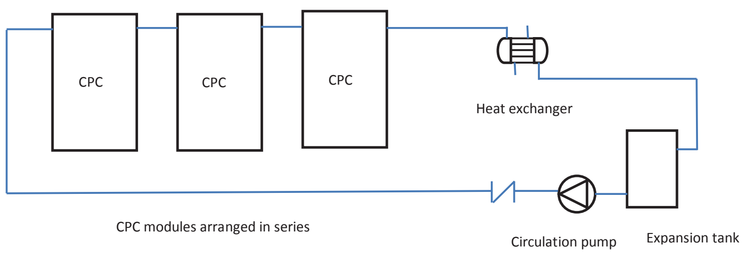


Figure 7: The general arrangement for the sensible heating of working fluid using CPC system

4. Steam generation from CPC system

Use of steam as a process working fluid for process heat has number of advantages like high heat carrying capacity, high heat transfer coefficient, constant temperature boundary condition during end-use heating, non-toxic, inexpensive, easily available etc.

There is limited literature about direct steam generation in a CPC in the recent past. Heinzel and Holzinger (1987) reported direct steam generation for process heat steam production from flat plate tubular collector. The steam generation from tubular collectors suffers from flow instabilities like steam blockage and flow pattern changes leading to vibration and unsteady release of steam (Heinzel and Holzinger 1987). The experimental setup of Heinzel and Holzinger (1987) was a natural circulating loop with heated riser glass tubes, release of the two phase flow in a steam drum and down comers to feed water back to the riser glass tubes. The experimental setup was operated with two modifications 1) use of orifice at the outlet of steam drum and 2) use of enlarge header for steam water separation at riser glass tube exist, both the modifications helped in curtailing flow instabilities.

El-Assy (1987) discussed the effect of a CPC thermal performance on steam exist condition (direct steam generation) using analytical equations. The effect of various parameters like concentration ratio, solar radiation, and mass flux on steam exit condition were predicted.

The challenges for direct steam generation in the CPC are as follows:

- Uniform water flow distribution in array of ‘U’ metal tubes enclosed in evacuated tube
- Steam lockout and flow instabilities in an array of the steam generating ‘U’ tubes
- High pressure drops for low pressure (low temperature) steam generation process
- Variation in solar radiation intensity leading to dry-out condition (100% steam dryness fraction) in individual tubes during operation

The challenges need detail investigations though experimentation for direct steam generation in the CPC system. The experimental measurements are expected to throw light on following aspects of direct steam generation from the CPC:

- Effect of variation in solar radiation on the different flow patterns in a tube boiling
- CPC solar collectors are generally mounted in an inclined position to maximize the intercept of solar radiation; the effect of inclination influences the transport processes in the bubbly and the intermittent flow regimes in two phase flow boiling.
- Two phase flow pressure drop, flow instabilities, wall temperature variations, control of dryness fraction under varying solar heat flux
- Source of two phase flow induced vibrations in the CPC system will be investigated
- The norms for acceptable water quality and steam exist dryness fraction will be studied to eliminate possibility of clogging of tubes

A suitable configuration for direct steam from the CPC will be developed considering various aspects investigated in experimental measurements

4.1 Experimental setup

CPC module mounted on the platform and integrated with supply line of water for direct steam generation will be the primary experimental setup. Schematic representation of experimental set up is as shown in Figure 8. The water at ambient temperature entering the CPC module will be heated from solar radiations. In order to study the steam generation in the CPC, there are two levels of measurement a) overall measurement of CPC module and b) local measurement of single tube

The overall measurement system consists of measurement of an inlet / outlet temperature to CPC modules, flow rate of water to CPC modules, heat flux incident on the CPC modules and dryness measurement of the outlet steam. The flowrate of water is measured with the amount of condensate collected in the tank. The heat flux incident on the CPC module is estimated based on global and diffuse radiation measured with pyranometer. The measurement of dryness fraction is discussed by Sardeshpande et al (2011). The analytical equations for experimental measurements are given in Appendix-A.

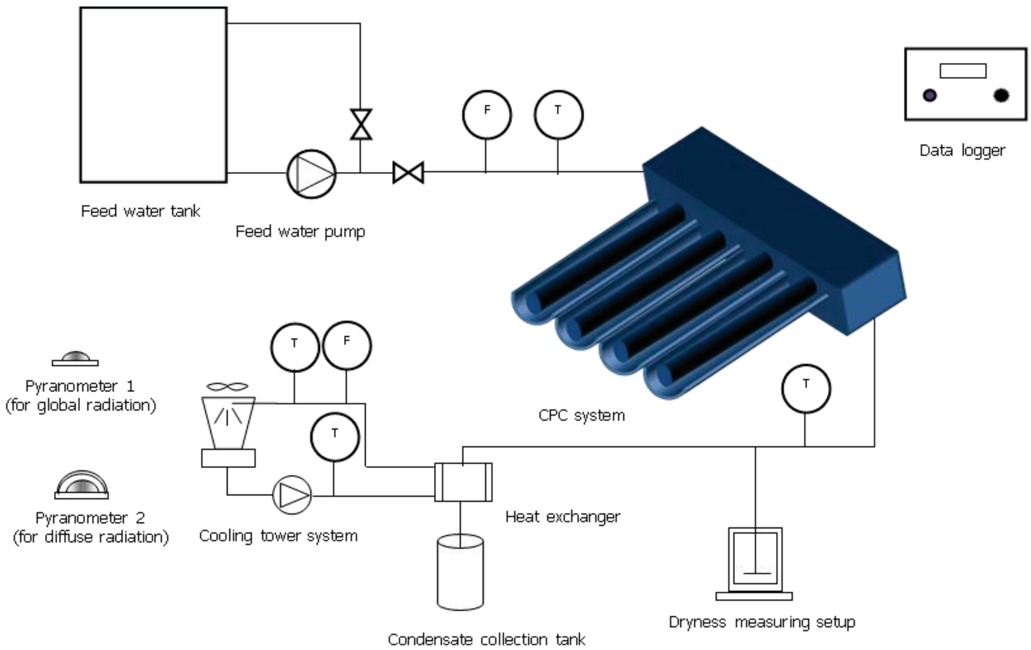


Figure 8: Schematic representation of proposed experimental set up

The local measurement consists of 10 temperature sensors installed along the length of a metal tube at an interval of 0.2 m distance. Along with this, two pressure sensors will be installed at the inlet and outlet of the tube to check the pressure fluctuations and overall pressure drop. The tube wall temperature as recorded by the temperature sensor will be the influenced by the heat transfer across the walls and formation of flow regimes inside the tube. The data generated by the temperature and pressure sensors will be recorded in data logger at suitable capturing frequency. The effects of solar radiation variations on steam dryness fraction and flow regimes in the tube will be investigated in this setup. The variation in tube wall temperature with solar radiation for constant mass flow rate indicates presence of different flow regimes. Schematic representation of local experimental plan is as shown in figure 9.

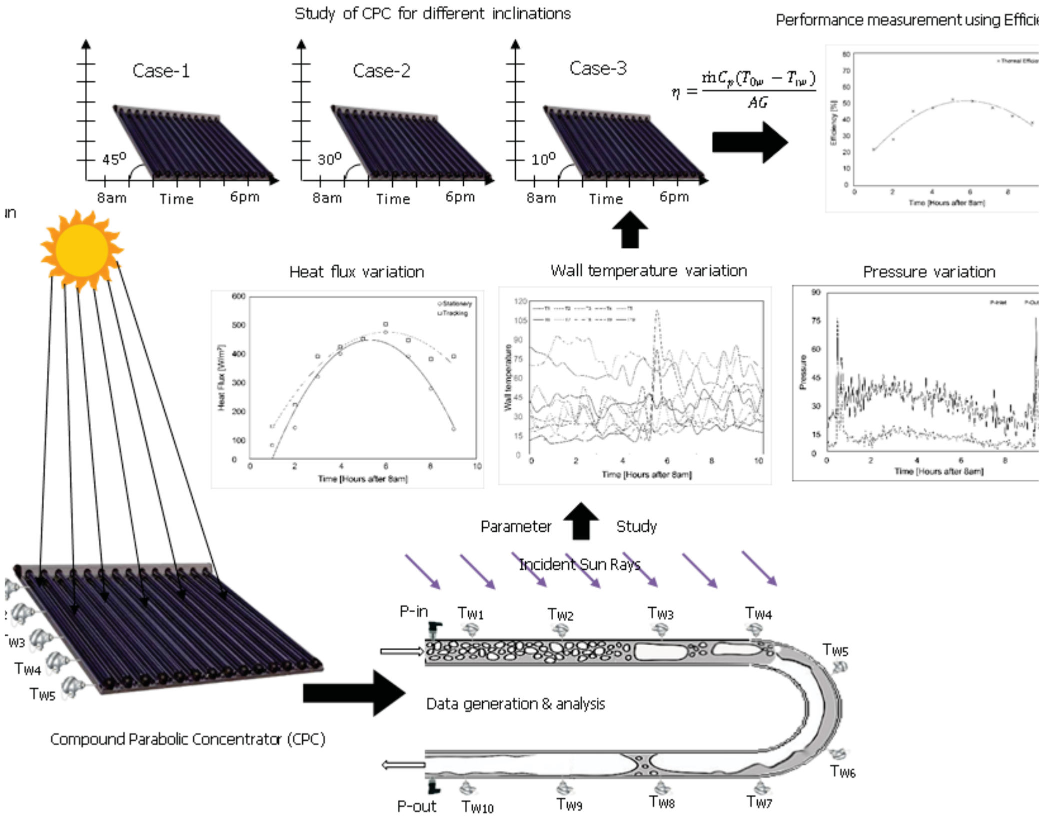


Figure 9: Schematic representation of Solar CPC and overall experimental plan

5. Conclusion

The direct steam generation from the CPC system has cost and operational advantages. However, it has many challenges on account of two phase flow in the metal tube enclosed in the evacuated glass tube. The two phase flow boiling patterns introduce flow instabilities and higher pressure drop. The present research work is focused on understanding and quantification of the direct steam generation in the CPC system.

The experimental setup proposed will undertake a) overall measurement of the CPC module and b) local measurement of single tube inside the CPC module. The overall measurement will be focused on the study of flow balances in various tubes, dryness fraction at the outlet of the CPC module for different solar radiation conditions and overall performance (thermal efficiency) of the CPC module. The local measurement of single tube will be focused on the wall temperature measurement along with mass flow rate of water and heat flux of solar radiation. The wall temperature will be used for the estimation of the boiling heat transfer coefficient. Experimental data analysis and understanding will be useful to develop direct steam generation engineering schemes and its integration approach with various process heat end-use applications.

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Appendix -A: **EXPERIMENTAL MEASUREMENT ANALYTICAL EQUATIONS**

The experiments on CPC will be conducted for different combination of inclinations, flow rates and solar heat requirement and according to the results obtained it will be put to optimum use. The plot of efficiency of the CPC collector against time will reveal the optimum time for the use of CPC. The theoretical energy calculations about the quantity of steam or hot water required, the capacity of the CPC to handle this load will be investigated on daily basis as per the following.

$$Q_u = \dot{m}_w \times (h_{g,out} - h_{f,in}) \quad (1)$$

$$h_{g,out} = (1 - x) \times h_{f,out} + x \times h_{fg,out} \quad (2)$$

where Q_u = heat gain during the steam generation (kJ)
m_w = mass flow rate of water (kg/s)
x = dryness fraction of steam generated
$h_{g,in}$ = Enthalpy of steam at saturation outlet temperature (kJ/kg)
$h_{f,in}$ = Enthalpy of water at saturation inlet temperature (kJ/kg)
$h_{f,out}$ = Enthalpy of water at saturation outlet temperature (kJ/kg)
$h_{fg,out}$ = latent heat of evaporation corresponding to saturation outlet temperature (kJ/kg)
The total energy received by the CPC depends upon the average solar radiation normal to aperture and the aperture area. The total solar energy received by the reflecting surface of the concentrator is presented in equation 3.

$$Q_r = A_{ap} \times I_g \times t \quad (3)$$

where Q_r = solar energy received (kJ)
I_g = normal beam radiation (kW/m^2)
A_{ap} = aperture area of concentrator (m^2)
t = duration of test (s)
The thermal efficiency of CPC is ratio of useful heat recovered to the total heat received on the aperture area as presented in equation 6.

$$\eta_{th} = \frac{Q_u}{Q_r} \quad (4)$$

η_{th} = Thermal efficiency of CPC

$$Q_{u,st} = \frac{Q_u}{N} \quad (5)$$

Where, $Q_{u,st}$ = heat gain during the steam generation for single tube (kJ)
N= Number of tubes

$$Q_{u,st} = \varphi_{avg} \times A_{sa,st} \times (T_{w,avg} - T_{f,avg}) \quad (6)$$

φ_{avg} = Average heat transfer coefficient for single tube (W/m^2K)
A_{sa} = Surface area of metal tube (m^2)
$T_{w,avg}$ = Average wall temperature of sensors (°C)
$T_{f,avg}$ = Average fluid temperature (°C)

The instruments used for testing are listed in table 3. The test setup also includes a steam dryness fraction measuring setup where a small amount of steam is introduced into an insulated container. This setup is adapted from the method proposed for measuring steam quality[25]. The change in the temperature is measured along with increase in weight of the water in the container. The mass balance of the sample taken for steam moisture measurement is given in equation 7.

$$m_s = m_{w,f} - m_{w,i} \quad (7)$$

where m_s = mass of steam in the sample for dryness measurement (kg)
$m_{w,f}$ = final mass of water after steam is bled in the container (kg)
$m_{w,i}$ = initial mass of water before sample of steam is introduced (kg)
After the estimation of mass of steam introduced in the container of the moisture measurement setup, the moisture fraction in the steam sample is estimated using the equation 8.

$$x = \frac{\lfloor m_{w,f} \times C_{p,w} \times (T_f - T_i) - m_s \times C_{p,w} \times (T_{sat} - T_i) + m_c \times C_{p,c} \times (T_f - T_i) \rfloor}{(m_s \times h_{fg})} \quad (8)$$

where x = dryness fraction of steam
$C_{p,w}$ = Specific heat of water (kJ/kgK)
T_f= Final temperature of water in container (°C)
T_i = Initial temperature of water in container (°C)
T_{sat} = Saturation temperature of water at the saturation pressure when test is conducted (°C)
m_c = mass of the container (kg)
$C_{p,c}$ = Specific heat of material of container (kJ/kgK)