A1 MW national solar thermal research cum demonstration facility at Gwalpahari, Haryana, India

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Concentrated solar power (CSP) plants have invited wide attention in various sunlight-rich regions around the world, including India. Under sponsorship of the Ministry of New and Renewable Energy, Government of India, the Indian Institute of Technology Bombay, Mumbai has conceptualized and carried out the basic engineering design, installation, commissioning and operation of a 1 MW(e) CSP plant in the campus of the National Institute of Solar Energy at Gwalpahari, near Gurgaon, Haryana, India. This is a unique facility integrating two different solar collector fields; direct steam-generating linear Fresnel reflector (LFR) field and conventional heat transfer fluid-based parabolic trough collector (PTC) field. It is a research-cum-demonstration facility intended to enable the development of future cost-effective CSP plants in the country. The design basis, brief description of the power plant, learning experiences during commissioning and operation of the plant, as well as preliminary performance results are presented here. The plant is grid-connected and operational. The preliminary results show low performance due to the lower optical efficiencies of both the collector fields, tracking error, loop imbalance of PTC field, and improper receiver size of LFR field.

Keywords: Concentrating solar power plants, linear Fresnel reflector, parabolic trough collector, research-cum-demonstration facility.

AMONG various solar thermal applications, concentrating solar power (CSP) is considered as a promising option and has invited wide attention[1–6]. India being a tropical country is blessed with abundant solar energy and hence can generate electricity through the solar thermal route. In recognition of this, the Government of India (GoI) has initiated an ambitious programme under the Jawaharlal Nehru National Solar Mission (JNNSM)[7] for generating 20 GW of electrical power using solar energy. Clearly, this requires the necessary development of knowledge base, manpower training and infrastructural facilities. In order to create awareness in the country and provide research and demonstration facility on solar thermal power, the Indian Institute of Technology Bombay (IITB), Mumbai had initiated a project in 2008 under sponsorship of the Ministry of New and Renewable Energy (MNRE), GoI. The objectives of the project were: (i) establishment of a national research facility on solar thermal power by installing 1 MW(e) grid-connected power plant; (ii) creation of a test facility for characterization of concentrating collectors, and (iii) development of a simulation software package for assisting the design of solar thermal plants. It is expected that the facility would help in opening up the black box on solar thermal power and lead to the development of indigenous capabilities. It would facilitate research and development for cost reduction of CSP plants. The facilities can be used to provide manpower training. This article presents the learning experiences on the commissioning and operation of the power plant and its preliminary performance results. The design basis and a brief description of the power plant are presented at the outset.

Design basis of the power plant

The design concept of the power plant is based on the assumption that the well-established route of power generation through Rankine cycle, using steam turbine, would be adopted. Consequently, the design basis evaluated different solar collector field configurations. Once the collector field is decided, the heat exchanger would be designed. A number of options for solar collector field were evaluated based on the thermal energy output and the corresponding cost. Three types of collectors, namely parabolic trough collector (PTC), paraboloid dish and linear Fresnel reflector (LFR) were considered. Figure 1 shows the proposed scheme. The process scheme consists of three storage vessels, namely the low-, medium- and high-temperature storage vessels. During start-up, all the oil stored in the low-temperature vessel would be pumped to the low-temperature trough solar field as well as the high-temperature trough solar field. The heated oil from the low-temperature field would go into the medium-

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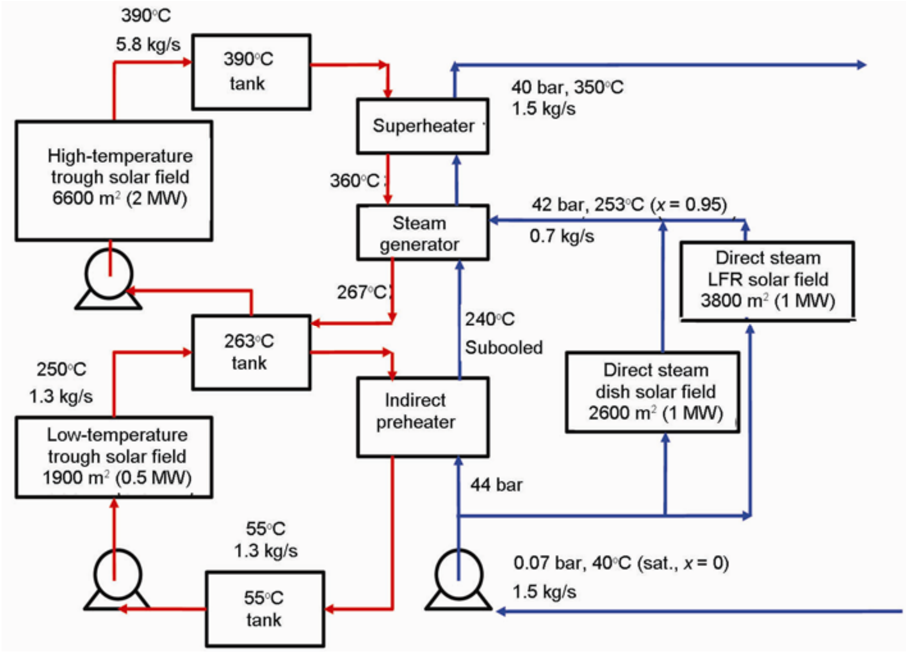

Figure 1. Schematic diagram of the proposed configuration.

temperature storage vessel and that from the high-temperature field would go to the high-temperature storage vessel. During normal operation, the oil stored in the medium-temperature storage vessel would be pumped into the high-temperature solar field, where it would be heated and then stored in the high-temperature storage vessel. Oil from the low-temperature storage vessel would be pumped to the low-temperature field, where it would be heated and stored in the medium-temperature storage vessel. Whenever the hot storage vessel is full, the oil would be allowed to pass through a series of superheater, evaporator and preheater exchangers, where the water would be converted into superheated steam (at 40 bar and 350°C).

The low-temperature solar field was found to be costlier. The lowest cost option was the LFR field, quoted by an Indian bidder with no experience in power generation. There was a bid for the PTC field from an international solar company with a solar power plant track record. It was decided to include both these options in the demonstration plant. Thus, 3 MW(th) parabolic trough field was ordered to a relatively experienced foreign bidder and 2 MW(th) to an Indian LFR bidder.

Description of the power plant

Figure 2 shows the block diagram of the power plant. The plant has been installed in the campus of the National Institute of Solar Energy (NISE), MNRE, GoI, at Gwalpahari (28°25′N, 77°09′E), near Gurgaon, Haryana, India. It consists of two different solar fields, storage tanks, heat exchanger and conventional power block components. The plant was developed as a research-cum-demonstration facility and therefore, it was decided to have a combination of two different solar fields; one field consisting of PTC with conventional heat transfer fluid (HTF) and the other field consisting of LFR with direct saturated steam generation.

PTC field

The PTC-based solar field with HTF circuit is an important component of the plant. It consists of parabolic trough concentrating collectors, the HTF pumps and expansion vessel (called LT vessel; see Figure 3 *a*). There are three parallel loops with four collectors in each loop. Each loop is arranged in two rows with U-type arrangement. The length of a row is about 240 m and the orientation is the NS direction[8]. Each collector is tracked using a hydraulic tracking system which includes a power pack and cylinders. These are controlled by programmable logic controllers (PLCs) located alongside the tracking system. The total aperture area of the PTC field is 8175 sq. m and the field is sized to deliver 3 MW(th) output at the design direct normal irradiance (DNI) of 600 W/m^2. DNI is the amount of solar incidence radiation received per unit area by a surface that is always held normal to the rays that come in a straight line from the direction of the Sun at its current position in the sky.

The main HTF pumps circulate the HTF through the PTC field. The rated flow of the pumps is 8.53 kg/s. During normal operation, the pump is expected to have a differential pressure head of 5 bar. The expansion vessel (LT vessel) of this plant mainly serves two purposes – to

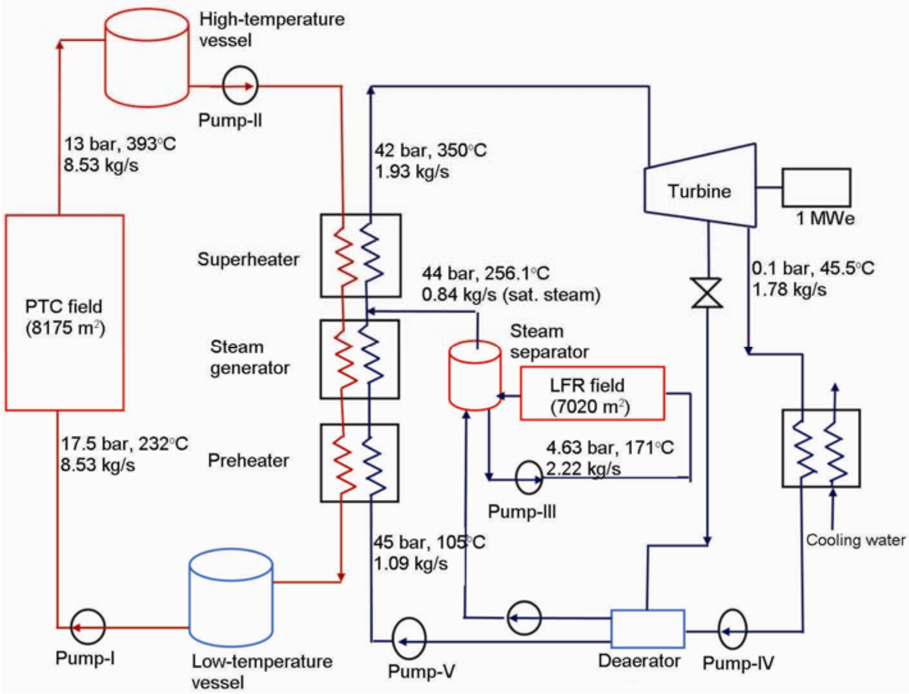

Figure 2. Block diagram of the power plant.

store the oil at a low-temperature (232°C) during normal operation of the plant and account for the volumetric expansion of the HTF. The vessel performs its task along with the storage vessel (HT vessel) in the HTF circuit. It operates at 13 bar pressure and is designed for 16.4 bar pressure. The vessel is nitrogen-blanketed and its volume is 16 m^3.

The HTF enters the PTC field at about 232°C and exits at 393°C. The outlet temperature of this solar field is maintained using flow control of the main HTF pump. As this is a feedback system, there are interlocks to avoid overheating of oil due to sudden rise in radiation. Temperature measurements are taken within the solar field and, if required, the field is partially defocused. Figure 3 *b* shows the PTC field installed at the site.

LFR field

The LFR solar field (Figure 4 *a*) consists of two LFR collectors oriented along the NS direction; each collector has eight rows of reflectors and a trapezoidal cavity receiver at a height of 12 m. Each reflector row is about 240 m long, while the receiver is about 260 m long. The receiver is made longer towards the north side of the field to intercept the reflected rays from mirrors during the period when the Sun is in the southern hemisphere. The total aperture area of the field is 7020 sq. m and is designed to deliver 2 MW(th) output at the design DNI of 600 W/m^2.

Saturated steam (at 44 bar and 256°C), generated by the receivers of two loops of LFR, is fed to a steam drum. The steam drum supplies dry saturated steam to the steam generator. The recirculation pump circulates the separated water from the steam drum through the LFR collectors. The feed water from the deaerator is supplied to the steam drum using the boiler feed pump (BFP-II). Figure 4 *b* shows the view of the LFR field installed at site.

Storage

The plant is designed without any fossil fuel-based auxiliary heating facility. The inherent variation and discontinuity in the output of solar fields, such as cloud cover and sudden changes in radiation level, can cause disruptions in the smooth running of the turbine and can also cause shutdowns during a day's operation. In order to account for such weather variations, a thermal storage has been included in the plant as buffer storage. Hot HTF from the solar field is stored in a pressure vessel (HT vessel) and used through the heat exchanger based on appropriate control logic. Volume of the HT vessel is 18 m^3 and it is designed to store hot oil at 393°C at a pressure of 13 bar, for providing 30 min of buffer storage. The HT vessel, similar to the LT vessel, is also nitrogen-blanketed. In order to reduce nitrogen consumption, the two vessels are pressure-equalized by a connecting nitrogen pipeline. Nitrogen-blanketing is done to provide an inert atmosphere and prevent contact of oil with oxygen at high-temperatures, which causes degradation of the oil.

Heat exchanger

The heat exchanger consists of three units, viz. preheater, steam generator and superheater. The hot HTF from the HT vessel first enters the superheater, then the steam generator and finally the preheater. The boiler feed water for the deaerator flows in the reverse sequence, that is, preheater, steam generator and finally the superheater. There are two bypasses for the heat exchangers, one overall bypass and another one only for the superheater. The overall bypass is required during the cold start-up. During the normal operation of the plant, the superheater bypass is not used. However, this bypass can be utilized in case of a need to control the degree of superheat for the steam going to the turbine.

The preheater is shell and tube (TEMA AEU) heat exchanger, sized for 0.61 MW(th) heat duty with the HTF on the shell side having single pass, and the boiler feed water is on the tube side with six passes. The steam generator is a kettle-type reboiler (TEMA AKU) with a rated duty of 2 MW(th). The HTF is on the tube side having six passes, and the steam and saturated boiler feed water are in the kettle-type shell. The steam generator also receives the saturated steam generated by the LFR solar field in the steam space of the kettle shell. Thus the mass of boiler feed water entering the steam generator is different from the steam coming out of the unit. The steam generator has a continuous and automatic blowdown. The continuous blowdown is set to a fixed blowdown flow. On the other hand, the automatic blowdown maintains the total dissolved solids (TDS) of the boiler feed in the shell, based on pH and conductivity measurements. The rated duty of the superheater (TEMA BEU) is 0.56 MW(th) with the HTF on the shell side having single pass and the steam is on the tube side with two passes. Figure 5 *a* provides a view of the heat exchanger installed at site.

Power block

The power block (Figure 5 *b*) consists of the turbine, generator, condenser and auxiliary equipment such as dump valve, condensate extraction pumps (CEP), ejector with

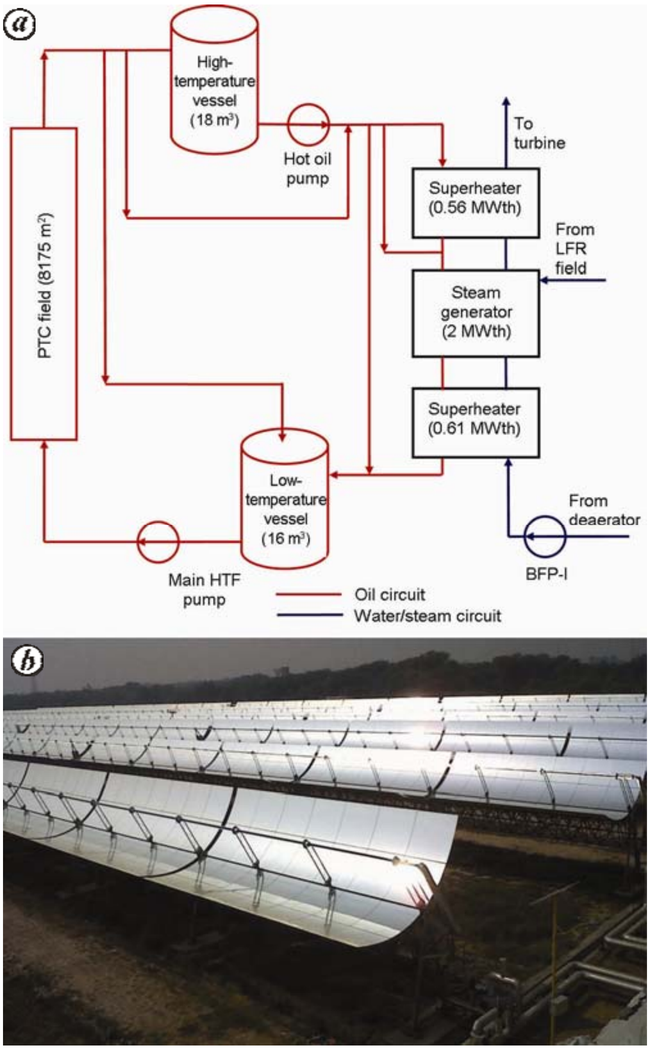

Figure 3. ***a***, Schematic diagram of parabolic trough collector (PTC) field. ***b***, PTC field installed at site.

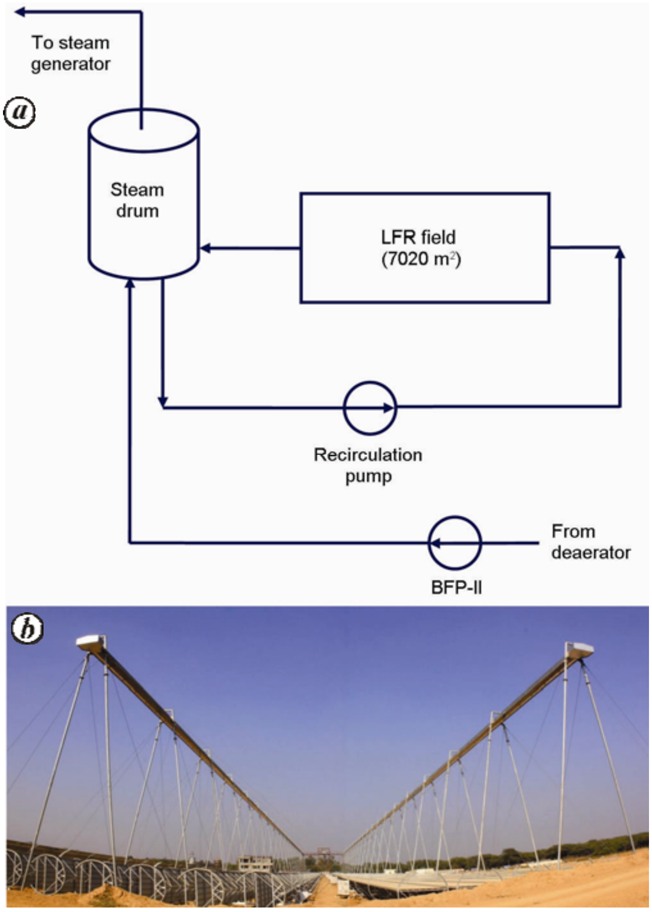

Figure 4. ***a***, Schematic diagram of Linear Fresnel reflector (LFR) field. ***b***, LFR field installed at site.

ejector condensers, gland vent condenser (GVC) and turbine hydraulic oil system. There are a number of other systems in the plant such as water treatment plants (softener and de-mineralized), boiler feed water system, auxiliary steam system, cooling water system and dosing system.

The turbine receives superheated steam (at 350°C and 40 bar) from the heat exchanger during normal operation. It has a parallel connection to the dump valve (bypass to the turbine), which is utilized during start-ups. Both the turbine and the dump valve are connected to the condenser. The condensate from the hotwell of the condenser is the suction end of the CEP. The CEP circulates the condensate through the ejector condensers and the condensate then flows to the deaerator.

The single-stage, single-bleed, condensing-type reaction turbine is coupled to a 1 MW(e), 415 V generator via a gearbox. The turbine is electronically governed by a Woodword 505 governor in a pressure-governed mode; that is, the pressure at the turbine inlet is maintained according to the signal from the controller. The turbine has a hydraulic system for cooling of bearing, gearbox and the governor actuator system. The main turbine outlet is connected to the condenser with an expansion bellow to the shell side of the condenser. The condenser is a shell and tube-type exchanger operating at a vacuum of 0.1 bar with single pass on the shell side and two passes on the tube side. Steam and condensate are on the shell side while the cooling water is on the tube side. At the rated condition, the condenser has a duty of 3.92 MW(th).

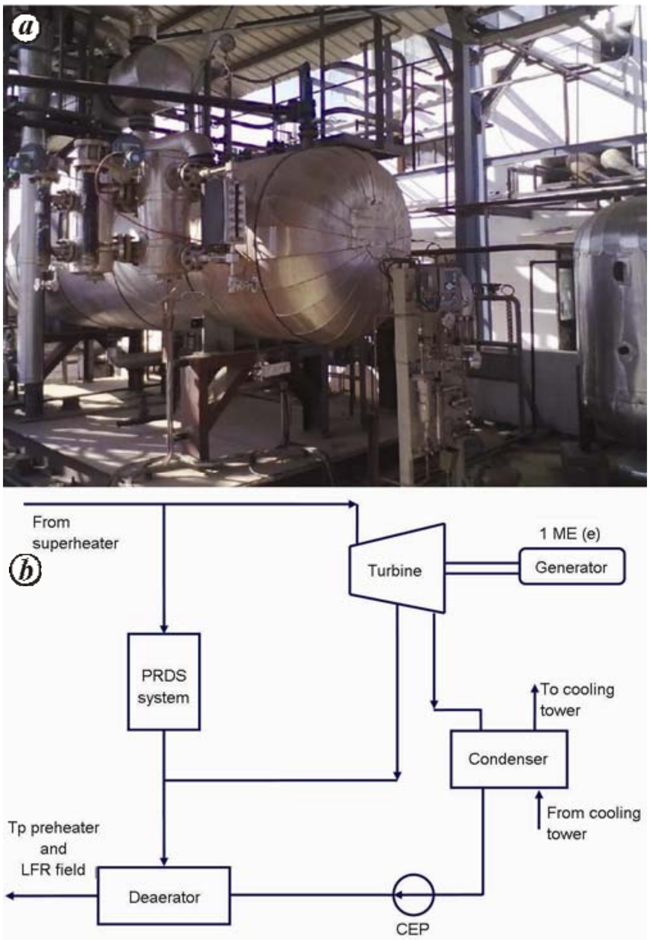

Figure 5. ***a***, Heat exchanger installed at site. ***b***, Schematic diagram of power block.

The CEP pumps the condensate from the hotwell to the deaerator via the ejector condensers and a control valve. The condensate acts as cooling water in the ejector condenser and the control valve controls the hotwell level. The outlet of the ejector condenser also has a minimum recirculation line back to the hotwell via a control valve. At the rated condition, the flow through the CEP is 1.78 kg/sec.

The ejector system has three ejectors – one hogger ejector and two condensing ejectors. The hogger ejector is used during start-up and it is open to the atmosphere. The two condensing ejectors are for normal working condition with one working and one standby. The condensing ejectors are connected to the ejector condenser. The condensate is sent to the turbine condenser through the expansion pipe. Figure 6 provides an aerial view of the IITB solar thermal power plant and test facility.

Learning experiences

There are several learning experiences in commissioning and operating the plant. These have been classified into three categories[9], viz. operational, equipment and system problems (Figure 7).

Operational problems

During commissioning of the plant, a few problems occurred in its operation. These were identified and solved at site.

Breakage of receiver glass window of the LFR system: The grid power supply at the site is erratic and whenever the grid supply fails, power from the diesel generator (DG) unit takes over. On one such occasion during the operation of the plant, the DG supply was not available. When the grid supply failed, the tracker of the LFR field got stalled. With change in the position of the Sun, the focus of the LFR system was partially shifted from the tubes to the enclosure. As a result, thermal stress was induced in the metal and the receiver glass window was broken. The position of the receiver is at a height of 12 m from the ground level and therefore, it was inconvenient to repair.

Water entry in instrumentation air line: Demineralization plant (DM) requires air supply for proper mixing of

Figure 6. Aerial view of the IITB solar thermal power plant and test facility.

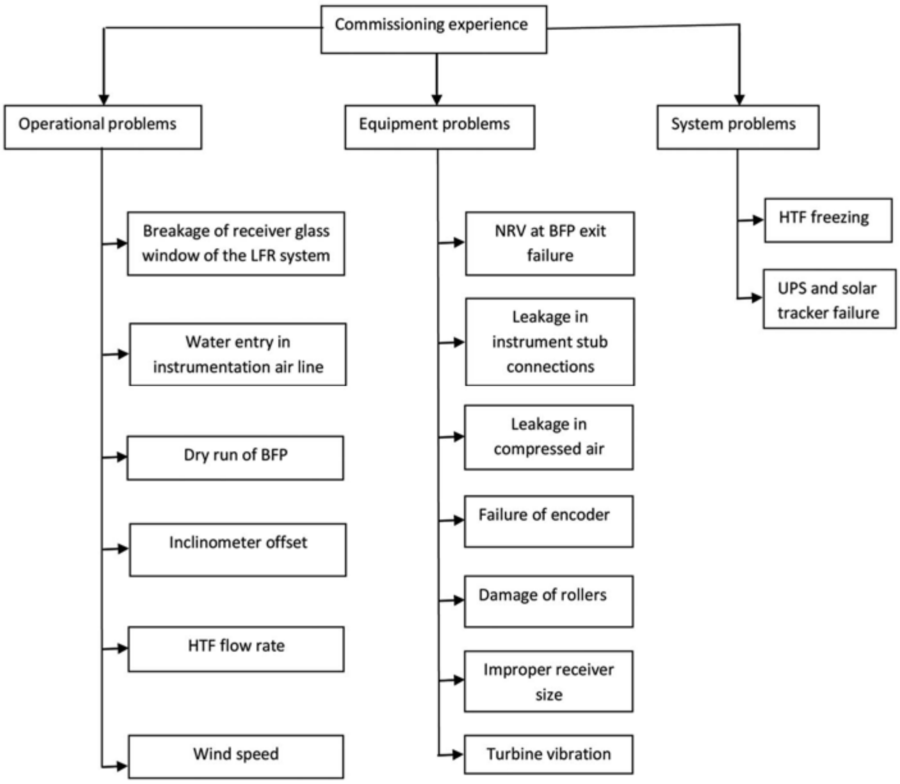

Figure 7. Experience in commissioning of solar thermal power plant.

resin in mixed bed unit. During commissioning, water from the DM plant entered into the air line. As a result the electro-pneumatic positioners of four control valves were damaged. The problem was solved after installation of an NRV in the compressed air line at the inlet of the DM plant.

Dry run of the boiler feed pump: The boiler feed pump (BFP) used in the power plant is a canned motor type that should not run dry for more than 2 sec. The BFP has suction from the deaerator and trips when the level in the deaerator falls below a minimum value. When the deaerator was being commissioned, it was observed that the BFP ran at full RPM, but the water level in the steam generator did not increase. Multiple runs were taken, but the problem persisted. The plant was shut down and the suction line was checked. It was found that there was no water in the deaerator even though the level transmitter of the deaerator showed sufficient water. The level transmitter had malfunctioned due to air ingress. Fortunately, the pump was not damaged and the level transmitter was recalibrated. To prevent such a problem, the control logic is now changed to trip the BFP with signals not only from the level transmitters but also from level switches in the deaerator.

Inclinometer offset: Inclinometers are used for setting the tilts of parabolic trough collectors so that proper focusing of reflected radiation at receivers is realized. It is found that the changes in the offset values for these inclinometers are needed quite frequently. On scrutiny, two reasons have been identified. The first is the general hazy sky condition at the site. Because of this, there occurs atmospheric refraction of solar radiation resulting in the change of apparent position of the Sun in the sky. Consequently, the regular expressions based on solar radiation geometry for locating the Sun do not work satisfactorily. Secondly, there is wear and tear in drive mechanisms of inclinometer resulting in the shifting of the image at the receiver. As a result, the inclinometers need to be adjusted on a regular basis for realizing proper focusing of reflected rays at the receivers of the parabolic trough collectors.

HTF flow rate: There are three loops (each loop having two rows with U-type arrangement) of parabolic trough collectors in the plant. It was noticed that there were significant differences between the outlet temperatures of these rows. The behaviour varied from morning to afternoon. On scrutiny of the vendor's recommendations, it was noticed that the rpm of the HTF pump was very low resulting in a very low oil flow rate. The flow rate was increased so that turbulent flow was realized in the receivers causing high heat transfer to the oil. This remedial measure partially decreased the differences in the outlet temperatures of three loops. However, did not completely solve the problem. The loop imbalance is one of the major reasons for lower performance of this field.

Wind speed: The structures of parabolic trough collectors are designed for a maximum wind speed of 19.5 m/s. However, the collectors go to safe position if the wind speed crosses 8 m/s. This hampers the operation of the plant, especially during summer months. While average wind speed may be below 8 m/s, the gustiness of wind may result in a peak higher than 8 m/s. Consequently, collectors move to safe position once the controller senses wind speed more than 8 m/s. In order to overcome this problem, the wind speed limit has been reset to 12 m/s based on the site data. Besides, a time delay is introduced so that the controller would respond if the wind speed crosses 12 m/s for more than 10 s.

Equipment problems

During plant commissioning, a number of problems were encountered with a few equipment. The errors in specification of the equipment have shown up as problems during commissioning of the plant. A brief discussion about the problems encountered, experiences and corrections made to solve them is provided below.

NRV at BFP exit failure: The heat exchanger was pressurized for the first time on 1 October 2012 using steam generated from the parabolic trough solar field. Subsequently, steam was being generated and blown to the atmosphere to clean the turbine inlet steam line. The BFP is operated based on the water level in the steam generator. When the steam generator (SG) water level reaches a reasonably high value (set as L_{max}), the BFP trips and is switched on when the level drops to a low value (set as L_{min}). On 27 October 2012 at about 1400 h when the heat exchanger was being pressurized (pressure – 25 kg/cm^2 (g), hot oil temperature – 274°C), steam was observed from the running BFP and vibration was also noticed in the deaerator. At this moment, the BFP was not running as there was sufficient water level in the steam generator.

A series of actions were taken immediately to prevent possible damage to the equipment. The boiler feed pump was isolated by closing the outlet gate valve; the vent valves were opened to decrease the pressure of the steam generator; the solar field was defocused and the heat exchanger was bypassed to limit steam generation. It was noticed that the suction line from the deaerator to the BFP was hot and water temperature in the deaerator increased from ambient (30°C) to 42°C, and the pipe supports on the suction line were dislodged. On examination, it was concluded that the vibration sound in the deaerator was due to the backflow of steam from the steam generator. The backflow of steam and hot water from the steam generator to the deaerator clearly indicated that the NRV at the BFP exit had failed. The NRV was welded on a vertical line, but it was suitable for installation only on a horizontal line. The problem occurred because of incorrect specification of the NRV and its installation. The NRV was replaced by an appropriate type mountable in vertical lines.

Leakages in instrument stub connections on heat exchanger: Temperature transmitters have been fixed on oil lines going into and out of the heat exchanger. The vapour pressure of Therminol VP-1 (Solutia Inc., Therminol VP-1 properties, St Louis, MO, USA) at 257°C is 1 bar (a). As temperature increases, the vapour pressure of the Therminol VP-1 increases. The pressure of the Therminol VP-1 in the circuit should be more than the vapour pressure and has to be maintained using nitrogen-blanketing on the pressure vessels.

During operation of plant when the HTF was heated to temperatures above 257°C, leakage was observed from temperature transmitter stubs. Upon inspection it was found that the HTF vapour was leaking from the screwed connection between the stub and the nipple of the temperature transmitters. The plant was shut down to prevent further loss of the HTF.

The end connections of the transmitter stubs were screwed together. Welding on the screwed connections with HTF in the line was not considered as auto ignition temperature of the HTF is 621°C, whereas the arc temperature of the welding is about 1000°C. Draining oil from the circuit was also not an option because the circuit was charged with approximately 20 tonnes of oil. Isolating the heat exchanger and locally removing the oil also meant removal of considerable volume of oil in the heat exchanger. Moreover, the valves isolating the exchanger passed a certain amount of oil due to which the exchanger can never be kept completely dry from oil. A vendor was identified to do on-line sealing of the stub (Leak Seal Experts India Pvt Ltd, 449/B, Mundka, Delhi). A metal clamp was put around the stub; the space between the clamp and the stub was injected with a sealant. The leakage was stopped and the plant operation resumed. Lesson learnt from the problem is that the HTF circuit should have minimum flanged and absolutely no screwed connections. Normally, complete welded connections are preferred for the HTF loop.

Leakages in compressed air piping: Compressed air is required in a power plant for operation of control and pneumatic valves. The desired air pressure for operation of these valves is 5–7 kg/cm^2 (g); as a result the discharge pressure at the compressor is about 7.5 kg/cm^2 (g). The compressed air piping network at the project site is made of galvanized vent (GI) with threaded end connection. Ideally, there should not be any pressure drop from the compressor storage tank discharge to the valve inlet. However, it was observed that gradually the pressure at the valve inlet started to drop to 1.5 kg/cm^2 (g) even though the pressure in the air storage tank was 7.5 kg/cm^2 (g).

On examination, it was noticed that there were significant leakages from the threaded ends of GI pipes and for continuous supply of air, the piping network needed to be tightened routinely. The entire network of compressed air was replaced by MS welded pipes during the plant shutdown for longer duration in winter. The lesson learnt is that piping network for compressed air line should be completely welded to minimize the leakages.

Failure of encoder: An encoder sends the feedback value to the supervising control and data acquisition (SCADA) system on the movement of reflector in the LFR system. The roller on which the encoder is mounted had slipped from the rotor. Consequently, the roller was stationary even upon reflector movement and no signal of the reflector movement was being communicated to the SCADA. On physical inspection, the slippage was noticed. It was also noticed that the roller surface was too slippery. The encoder was re-fixed. The lesson learnt is that care should be taken to avoid spread of lubricating oil.

Failure of rubber rollers: The surfaces of a few rollers in the LFR system were damaged due to high-temperature in summer. The rubber part of the roller cracked and peeled off from the metal hub. This resulted in improper movement. Rollers made up of materials other than rubber were used in place of the defective ones to avoid this problem.

Improper receiver size: There is a mismatch between the size of the receiver of the LFR and its image. The receiver size is smaller than the image size, resulting in irradiation of the support structures of the receiver. This had caused differential expansion of structures resulting in breakage of the receiver glass cover. This is a design fault and hence cannot be rectified at the operation stage. However, in order to tackle this problem during operation, one reflector-row in the east side of the LFR field is not focused in the morning and one row in the west side is not focused in the late afternoon. This results in a performance penalty.

Turbine vibration: The turbine is tripped-off when its vibration crosses 200 μm. The excessive vibrations may damage components such as turbine seal, blades and bearings. During commissioning of the plant, excessive vibrations more than 200 μm were noticed. While the turbine manufacturer examined the turbine settings and corrected them, a few modifications were made in the pipe supports and connections of the steam line with the help of a piping consultant. The modifications included replacement of a bend near the turbine by ‘T’ joint with steam trap and drain arrangement so that the condensate does not enter the turbine. Moreover, a couple of additional supports were provided, including a support of resting and guide (RG)-type for restricting movement in a particular direction, while allowing in the other direction. With these measures, the vibration of the turbine was reduced and remained with safe limits.

System problems

Power and water are the two critical resources for construction and commissioning of a power plant. The plant has a bore-well facility in its boundary and a dedicated power line to the substation to evacuate power from the plant. The same line is used for meeting the electricity load of the plant in case it is not evacuating power. However, during the construction phase of the plant, this line was not available and the power requirements were being met by a tapped connection from the nearby substation. However, due to heavy load-shedding this line proved to be unreliable. This resulted in problems as discussed below.

HTF freezing

The crystallization temperature of HTF (Therminol VP1)[7] is 12°C. The plant, located at Gwalpahari, near Gurgaon experiences minimum temperature much below 12°C during winter. Figure 8 shows the ambient temperature

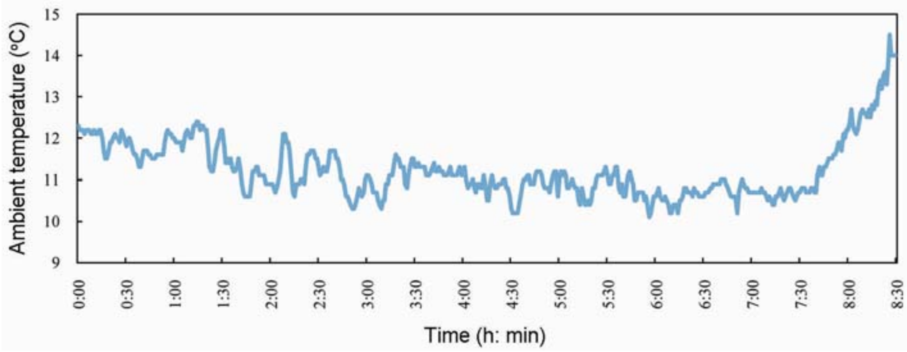

Figure 8. Ambient temperature profile at the project site on 24 February 2013.

profile at the project site from midnight (2400 h) to 0830 h on 24 February 2013. It can be observed that, for most part of the night, the temperature is below 12°C. The plant runs in antifreeze mode during winter, in which the oil is continuously circulated in the solar field and heated to 40°C by an inline heater and electrical heat tracing provided at the pump suction and discharge lines.

The HTF pump was being used to circulate oil in the solar fields and pipe lines. However, due to unavailability of electrical power, a DG set was used to run the plant in antifreeze mode periodically depending on the reading of the temperature gauge at pump discharge. When the oil temperature in the gauge reduced below 35°C, the main HTF pump and electrical heating system were switched on. This activity was performed routinely for more than a month. However, on the evening of 31 December 2012, it was noticed that when the pump was started, it went to 150 rpm and the speed dropped to 9–10 rpm. The same procedure was tried again next morning; however, the problem persisted. It was observed that the pressure readings at the pump discharge and solar field outlet were 12 bar(g) and 3.2 bar(g) respectively. It was concluded that the HTF was crystallized in the circuit and the pump could not circulate the oil in the circuit. On 15 February 2013, when the ambient temperature was more than 20°C, the main HTF was started again. However after multiple runs on that day, the seal in the main HTF pump failed and oil started leaking from the seal pot. Similar problem was experienced when one storage tank pump was started.

On scrutiny, it was found that the HTF pump was run based on the observation of one temperature gauge. The temperatures in the field and at other locations could not be monitored by the operator since the PLC of the parabolic trough system was not working at that time. It is likely that the freezing of oil might have taken place somewhere in the circuit, resulting in the failure of the pump. This problem could have been avoided by running the antifreeze operation round the clock. This was however not done in order to save on diesel cost. The seals of the main HTF pump and storage pumps were replaced and the pumps were tested after the unfreezing of oil in March. It is recommended that the system should run in antifreeze mode round the clock during winters and it is important to monitor the oil temperature at all locations in the circuit. It may be mentioned that the pump seals do not have antifreeze protection. As a result only the inline pump is protected from the oil crystallization, while the oil in the seals of stand-by pump crystallizes. Further, two storage tank pumps are used only when oil is to be pumped into the circuit. Hence they cannot be run in antifreeze mode because they do not form a loop, unlike the main HTF pump. Therefore, because of the current system and current pump seal design, oil in the seals of three out of four HTF pumps crystallized. The solution to this problem is to use canned pumps in the plant and running in antifreeze mode during winter.

Uninterruptible power system and solar tracker failure: Uninterruptible power system (UPS) system is installed for emergency back-up to the PLC and weather station. A standalone UPS system sustained the load for 6–8 h. However, since the grid power was not available and the DG system ran intermittently for antifreeze mode, the solar tracker (measuring the radiation data) was found to offset daily. As a result, the worm gear in the tracker failed and the tracker stopped working. The UPS was being used for larger duration while it was meant to be operated only for a few minutes, in the case of grid failure. This resulted in decreased back-up period of the UPS. The problem could be sorted out only after continuous power back-up.

Performance of the plant

The preliminary performance results of the plant are now presented. The grid synchronization of the plant was carried out in May 2014. The plant does not have any auxiliary source of heat and hence the turbine is shut down in the late afternoon when the DNI reduces significantly. Similarly, the turbine can be started only a few hours after sufficient Sunshine is available in the morning hours

Table 1. Performance evaluation of the plant on 4 June 2014

Date	Time duration for field operation (h)	DNI $(W/m^2)_{avg}$	$Q_{gain,avg,PTC}$ (kW_{avg})	$Q_{gain,avg,LFR}$ (kW_{avg})	$P_{e,avg,gross}$ (kW_{avg})
4 June 2014	10.00–11.00	650	1398	–	–
	11.00–12.00	641	1901	1621	–
	12.00–13.00	596	1874	722	196
	13.00–14.00	637	2203	873	382
	14.00–15.00	636	2244	1153	409
	15.00–16.00	597	1864	965	303

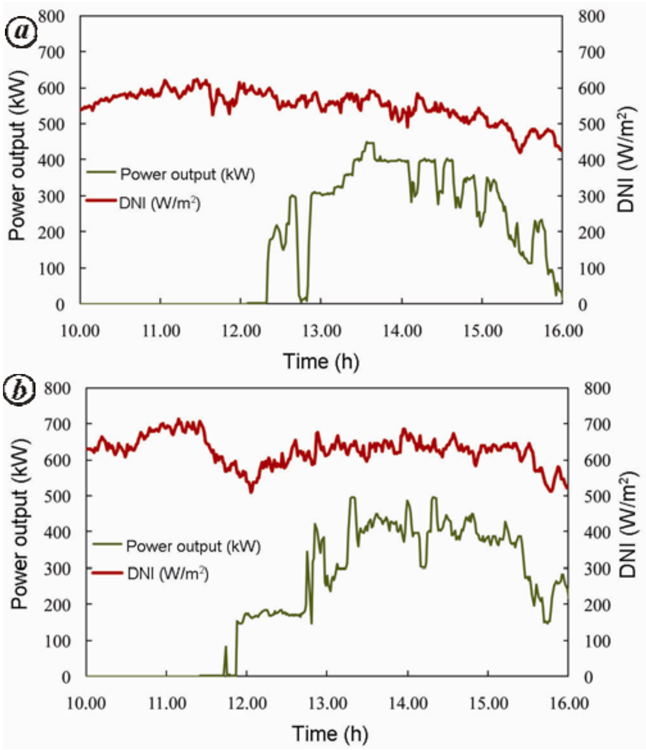

Figure 9. ***a***, Minute-by-minute turbine power output data for (***a***) 28 May 2014 and (***b***) 4 June 2014.

to heat oil in the PTC field and generate steam in the LFR field. Thus, the turbine is typically operated, and hence the power is generated, for only about 4–5 h daily. This may again vary depending on the sky condition and the availability of DNI. Besides, power can be fed to the grid if it remains live during the turbine operation. The grid supply was erratic at the site during the commissioning period.

In order to get more insight, Table 1 provides the hourly average output of the PTC field ($Q_{gain,avg,PTC}$), LFR field ($Q_{gain,avg,LFR}$), and turbine-generator ($P_{e,avg,gross}$), for 4 June 2014. The DNI, PTC field, and turbine data are recorded at an interval of 1 min. However, the LFR field data are recorded at an interval of every 10 s. Based on these raw data, hourly average performance of the plant is calculated. As shown in Figure 9, the instantaneous values of the power output fluctuate rapidly. Therefore, the hourly average performance data are reported. It is observed that the maximum hourly average power output of 409 kW(e) (on 4 June 2014 for the duration 14.00–15.00 h) is achieved by the plant, which is lower than the design value of 1 MW(e). The maximum instantaneous power output by the plant is about 650 kW(e) (on 27 May 2014) during the commissioning stage.

Figure 10 shows the heat and mass balance diagram (HMBD) of the plant, for the time duration 14.00–15.00 h on 4 June 2014. During the commissioning phase of the plant, the PTC field is operated with fixed-flow mode, resulting in variation of outlet temperature with DNI. During normal operation of the plant, the PTC field will be operated with fixed-temperature mode, resulting in variation of flow rate through collector field with DNI to maintain the outlet temperature at about 390°C. The oil-side flow meters at the inlet of superheater and outlet of preheater showed incorrect readings and therefore, the flow rate given by the flow meter after the main HTF pump (pump-I) was taken for the HTF circuit. The high-temperature (HT) vessel operated in the level-maintaining mode during the commissioning phase of the plant, resulting in almost same flow rates at the inlet and outlet of HT vessel, which validates this assumption. Moreover, the steam/water side flow meters at the outlet of superheater and condenser also showed incorrect readings and the flow rate at the outlet of superheater/inlet of turbine was back-calculated based on the Willans' line equation given by the turbine manufacturer.

Figure 11 shows the Sankey diagram representing the energy flows and the losses of various components of the plant, based on plant operation during 14.00–15.00 h on 4 June 2014. The major losses occur in both the collector fields (PTC field loss, 30.6%; LFR field loss, 34.3%) and power block (27.3%). It is expected that the collector fields losses will reduce significantly once the power plant operation is streamlined.

Table 2 presents the performance evaluation of main components of the plant, for time duration 14.00–15.00 h on 4 June 2014. The efficiency comparisons with design efficiency have also been done (Table 2). The efficiency of the PTC field is calculated to be 43.2% instead of design efficiency of 61.2%. The possible reasons for lower performance compared to the design conditions are improper loop balancing (Figure 12), tracking error and lower optical efficiency of the concentrators. The efficiency

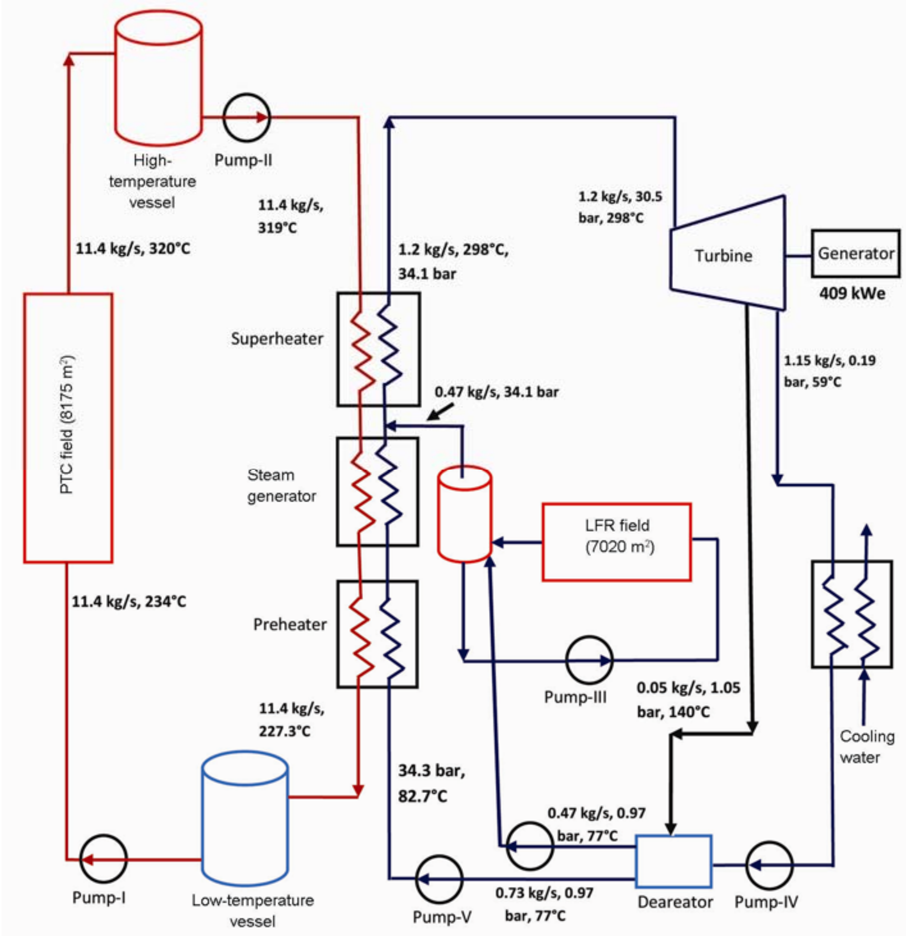

Figure 10. Heat and mass balance diagram of the plant for the time duration 14.00–15.00 on 4 June 2014.

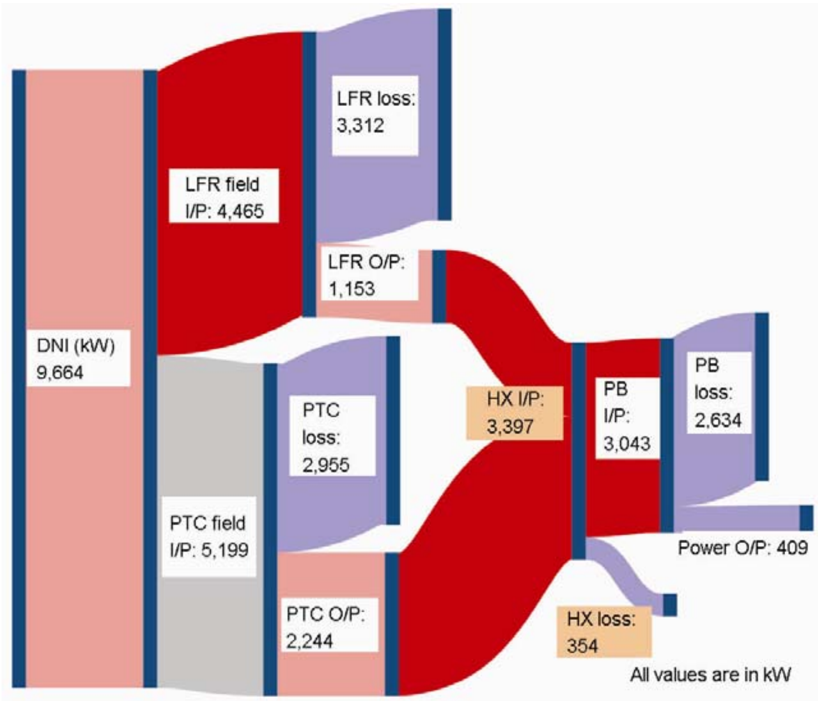

Figure 11. Sankey diagram for the time duration 14.00–15.00 on 4 June 2014.

Table 2. Performance evaluation of main components of the plant for time duration 14.00–15.00 h on 4 June 2014

Equipment	Design efficiency (%)	Actual efficiency (%)	Possible reason for deviation
PTC field	61.2	43.2	Improper loop balancing, tracking error and lower optical efficiency of concentrators.
LFR field	47.5	25.8	Lower optical efficiency of reflectors, improper receiver size and fluctuations of heat exchanger pressure at the commissioning time, as the overall operating strategy of the plant was not stabilized.
Power block	20 (Steam flow rate 1.93 kg/s)	12 (Steam flow rate 1.2 kg/s)	Lower performance of both the collector fields affects the turbine performance significantly as the part-load efficiency of steam turbines, especially for small size (1 MW(e)), is much lower.
Overall plant	11	4.5	Lower performance of both the collector fields and lower part-load efficiency of steam turbines.

PTC, Parabolic through collector; LFR, Linear Fresnel reflector.

Table 3. Performance evaluation of the plant

Date	Time duration for field operation (h)	Incident solar energy (kWh)	$Q_{gain,PTC}$ (kWh)	$Q_{gain,LFR}$ (kWh)	Time duration for power generation	$P_{e,gross}$ (kWh)
22 May 2014	10.00–15.00	53,236	7708	4919	11.00-15.00	326*
27 May 2014	10.00–16.00	51,806	12176	2935	12.00-16.00	860
28 May 2014	10.00–16.00	50,157	10930	4802	12.00-16.00	1041
29 May 2014	10.30–15.30	42,862	8321	3536	12.30-15.30	503*
2 June 2014	11.00–15.00	33,140	6987	2951	12.00-16.00	522
4 June 2014	10.00–16.00	57,074	11484	5334	12.00-16.00	1290
5 June 2014	10.00–15.00	43,335	9053	896**	12.00-15.00	405

*Failure of grid; **LFR under partial maintenance.

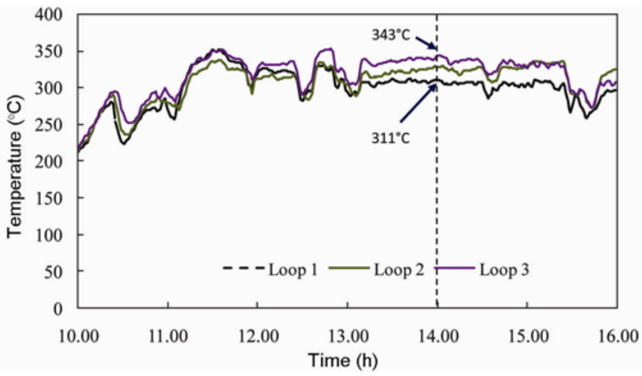

Figure 12. Typical loop imbalance problem in PTC field (4 June 2014).

of the LFR field is calculated to be 25.8% instead of design efficiency of 47.5%. The possible reasons for lower performance of the LFR field are lower optical efficiency of reflectors, improper receiver size and fluctuations of heat exchanger pressure at the commissioning time, as the overall operating strategy of the plant was not stabilized. It may be noted that the indigenous LFR manufacturer was executing the system for the first time at a commercial level. Lower performance of both the collector fields affects the turbine performance significantly as the part-load efficiency of steam turbines, especially for small size (1 MW(e)), is much lower. Therefore, the calculated efficiency of the overall power block is 12% instead of design efficiency of 20%. Finally, the overall plant efficiency is about 4.5% instead of design efficiency of 11%.

Table 3 presents results of a few days in May and June 2014 during the commissioning period. The time intervals during which the plant was operated, the thermal output of the PTC field ($Q_{gain,PTC}$) and the LFR field ($Q_{gain,LFR}$) as well as corresponding hourly DNI values are also shown in the table. It also shows the number of hours for which the turbine was operated and the quantity of gross power ($P_{e,gross}$) generated. The average output of the PTC field for seven days of operation, is about 59% compared to the expected output. It may be noted that the expected output, over a day, is calculated using the off-design performance data given by the manufacturers. The possible reasons for lower performance than expected are same as given in Table 2. The measured value of thermal output for the LFR, for seven days of operation, is about 45% compared to the expected output. The indigenous LFR manufacturer was executing the system for the first time at a commercial level and hence the part-load characteristics of the field were not known correctly. As mentioned earlier, the lower performance of both the collector fields significantly affects the turbine performance.

Summary

A CSP plant (1 MW(e)) was conceptualized, designed, installed and commissioned at NISE. The unique features of this CSP plant are the integration of a direct steam-generating LFR field with conventional HTF-based PTC field, buffer storage and no auxiliary energy source. During the commissioning stage of the plant, the maximum power generated was 640 kW(e). The preliminary results show that the collector fields have lower performance. The efficiency of the PTC field is calculated to be 43.2% instead of design efficiency of 61.2% and the efficiency of the LFR field is calculated to be 25.8% instead of design efficiency of 47.5%. The reasons for the reduced performance are lower optical efficiencies of both collector fields, tracking error, loop imbalance of the PTC field, and improper receiver size of the LFR field. The plant performance is expected to improve as these problems get resolved.

The learning experiences related to operational, equipment and system problems have been listed here and their solutions are shared. These experiences can help engineers in design, engineering, commissioning, and operation of future CSP plants. The plant has been connected to the grid and is operational. The NISE can use this facility for research and manpower training purposes. A national research facility on solar thermal power has been established by installing one 1 MW(e) grid-connected power plant, creating a test facility for characterization of concentrating collectors, and developing a simulation software package. This facility would enable the development of future indigenous CSP capability in the country.

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