SOLAR CONCENTRATION APPLIED TO OIL HEATING: AN EXPERIMENTAL FOCAL TUBE ENHANCED DESIGN

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Abstract. *The paper presents experimental results for a study about heat transfer effects from solar concentration over flow resistance of oil. In this study specifically, it is described and tested three different designs for the focal tube installed on a parabolic solar concentrator. In this arrangement, working fluid is heated in a primary cycle and the heat is transferred to the oil in a secondary flow cycle. At now, just the enhanced heat transfer to the working fluid of primary cycle is evaluated. The pressure loss reduction due to the oil flow heating will be estimated in future, aim to estimate the technical viability analysis of such arrangement.*

Keywords*: solar energy, alternative energy, heavy oil, solar concentrator, parabolic concentrator*

1. INTRODUCTION

The growing shortage of natural energy resources like coal and crude oil associated to the global heating due to the burning of such fossil fuels is commonly used as stimulation to new energy sources development, obviously emphasizing those renewable and non-polluting.

In such category it is included solar energy, which is a clean and abundant energy available in nature. Although the use of such font is still not spread in industrial environment, its utilization increase more and more in residential or small load applications.

In spite of Brazil be a country between tropics, the average solar irradiation over its territory varies from 400 to 700 W/m² year averaged [Cometta (2004)] in contrast to other countries located in similar latitudes as Australia, for example, that receives irradiation taxes around 1.300 W/m² in deserted areas. Figure 1 indicates the solar irradiation level for several areas on the globe, known as "solar belt."

In some regions of Brazil, especially in northern of Espírito Santo state and areas located on North-East states, it is very usual the occurrence of clean sky days, as well as the occurrence of heavy and extra-heavy oil production. Due to that, the development and improvement of technologies to promote heating from solar radiation in the exploration and transport of petroleum products can be a way for reducing costs, creating a more ecologic correctly operation, still allowing its development application to other industrial activities.

The main goals are associated to costs reduction as much of simplification in operation like maintenance practices for example, supplying a heating option in wild areas no-assisted by the conventional electric net.

By the moment, the aim of the present paper is to show the developments in a technology to reduce the conventional energy consumption of heavy oils pumping by the using solar heating. The prototype sketch proposed by this work is shown as a closed circuit in Fig. 2.

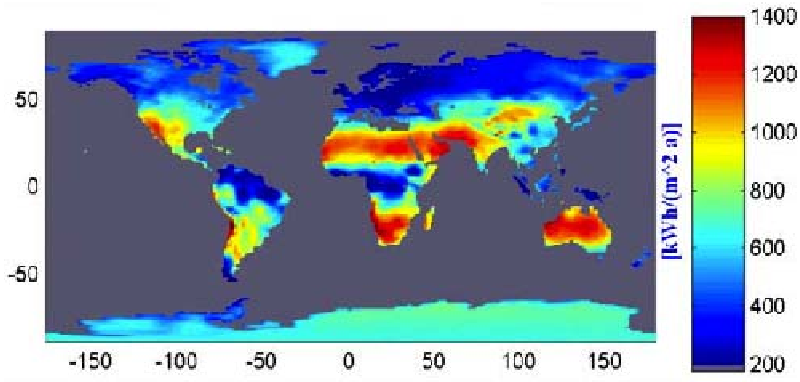

Figure 1. Solar irradiation tax on the globe

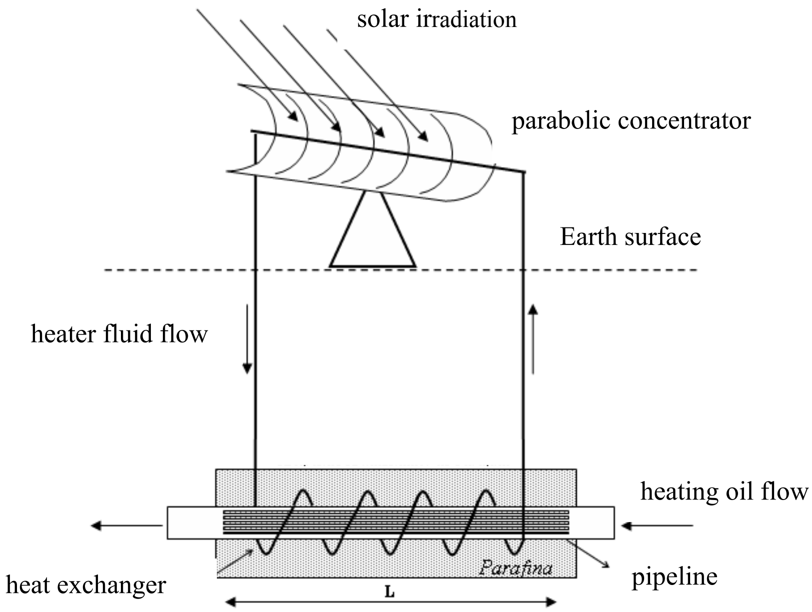

Figure 2. Sketch of the proposed solar heater system

2. BIBLIOGRAPHICAL REVIEW

Among the bibliography found to the development of this work, it is considered of larger contribution the research developed by Su and Estefen (2005) that propose electric heating of underwater multilayered composite pipelines used to enhance flow of heavy oil. The aim was to evaluate the pressure drop between the pit and the sifter as well as the power requested by such process. Theoretical simulations indicate significant reduction in pressure drop by heating, with consequent reduction of pumping power. In that case, it was obtained power reductions from 10 to 31.1%.

Representative information was supplied by the work of Trp (2005) in which, besides the non-dimensional modeling of the solidification and melting phenomena of the paraffin, it is also evaluated the heat exchange with respect to Prandtl number. The model proposed by Trp (2005) may be applied to analyses and further simulations of the heat storage process in later stages of the present project.

The work developed by Wang, Ruzhu and Wu (2004) investigated the heat exchangers experimentally for crude oil heating using solar energy. The information came to fortify the idea of the present project, considering the obtained results. In referred work, it were gotten elevations in oil temperature from 25°C to 30ºC, using heating from plane solar collector as energy source, which usually supply lower operation temperatures than those obtained by parabolic solar concentrators, as proposed here.

For conception, project and assembly of solar concentrators and correlated systems, it were used the class notes from the course of solar energy offered by Instituto Tecnológico y de Estúdios Superiores de Occidente – ITESO (1995) in Mexico and the work of Pérez (2005), which were of crucial importance.

The class notes from ITESO (1995) give detailed information about the phenomena involved with solar energy systems and also evaluate models and their respective applications. On the other hand, the Pérez (2005) paper brings information and technical details for solar concentrators as methods seeking to increase the heat reception and focal concentration, for example.

In the work of Dogruoz, *et al.* (2005), experiments were performed aiming to find the heat transfer and pressure drop characteristics at laminar flows in a duct with in-line square pin fin, and a correlation of the number of Nusselt to flows with very low Reynolds number, between 230 and 550. Such knowledge is used as part of the developments.

Many theoretical fundamentals on the subject about solar energy were obtained from Palz (1981) and Acioli (1994).

Dimensions and precise assembly and operating details specifically to the present work can be found in Gasparini and Louzada (2006). In Ramos *et al.* (2007) it is found earlier results for this project for an open cycle working fluid and distinct focal tubes arrangements than those proposed here.

3. SOLAR CONCENTRATOR CHARACTERISTICS

The equipment can be divided in three main parts: (a) parabolic mirror; (b) focal tube; and (c) circulation system, which is composed by pumps, temperature and flow measurement of working fluid.

The parabolic mirror should have specific and well defined characteristics in such way to optimize the capture and reflection of solar energy to the parabolic focus. Thus, as much the project as the construction of the mirror should obey rigid criteria in way to obtain, at the end of the construction, a curve which represents the projected parabola, in fact. It should be observed that the mirror may be set up in an inclinable structure, rigid enough in a way to preserve the parabolic shape during the positioning and inclination operations. Some geometric data can be see in Fig, 3.

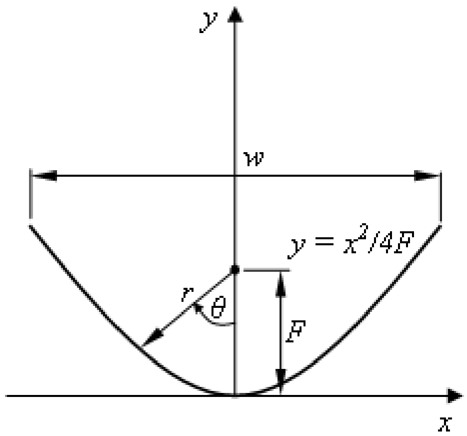

Figure 3 – Geometric data about curve shape selected to the mirror, where focus lenght F = 0,2m, w=1m and L=2m

As a reflecting surface (mirror) a fine polished plate of stainless steel, with small thickness was used because of its good reflectivity. To give the desired parabolic shape to this plate, a strong wood structure was mounted with the designed parabolic shape, as shown in Fig. 4a,b.

(a) (b)

Figure 4 - (a) Parabolic wood structure under construction, (b) Reflecting surface installed on wood structure

The mirror is completed with the positioning instrumentation in relation to the sun: transferrer, solar pointer, solar clock, compass and a movable base, seeking to facilitate the transport. In this paper, it will not be made any analysis to optimize the mirror operation, which will be used in all measurements related to the focal tube. Figure 5 displays the solar concentrator at work.

Figure 5 - Solar concentrator at work

The circulation system of water used in the tests is composed by a closed circuit where ordinary water flows from an insulated tank to the focal tube. The flow is measured by a rotameter, and the following temperatures are monitored: T1 (entrance temperature in the focal tube), T2 (exit temperature in the focal tube) and T3 (entrance temperature in the insulated tank). Figure 6 display the schematic drawing of the circulation system. The rubber hoses used before and after the focal tube were covered by thermal isolation, avoiding larger thermal losses to the atmosphere.

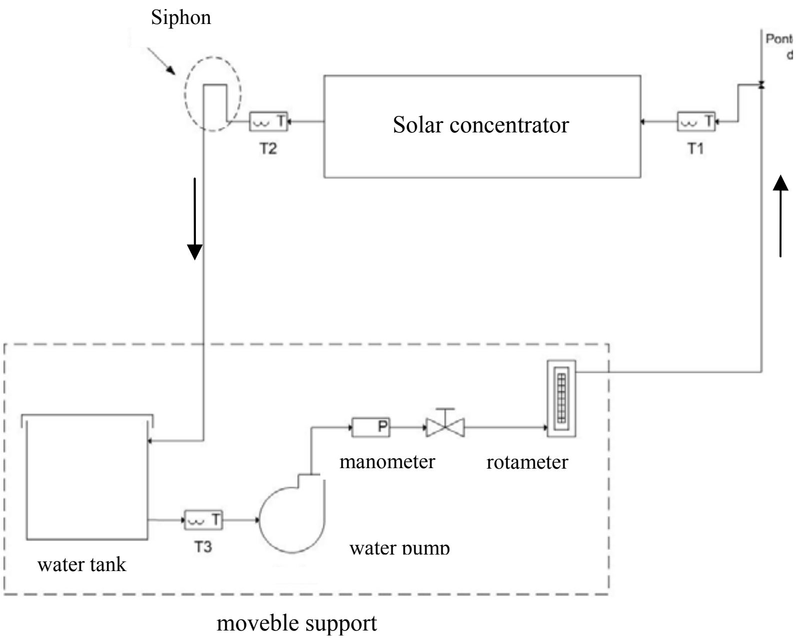

Figure 6 - Schematic draw of closed water circuit

On the other hand, the focal tube should have characteristics that minimize its thermal resistance. Thus, a commercial tube of copper (Ø 3/4", L=2.0m) with thin walls was selected, in way to reduce the thermal resistance due to heat conduction. However, the focal tube is exposed to atmosphere, providing a heat transfer reduction to the working fluid due to forced convection promoted by wind. The enhanced heat transfer related to convection reduction from tube design is the object of the present analysis.

According to Fig. 7, it were proposed and built three different designs for the focal tube:

- Tube1: Black tube of copper covered by a thin thick glass tube.
- Tube2: Black tube of copper with internal in-line square copper pin fins installed inside, covered by a thin thick glass tube;

- Tube3: Black tube of copper directly exposed to the atmosphere;

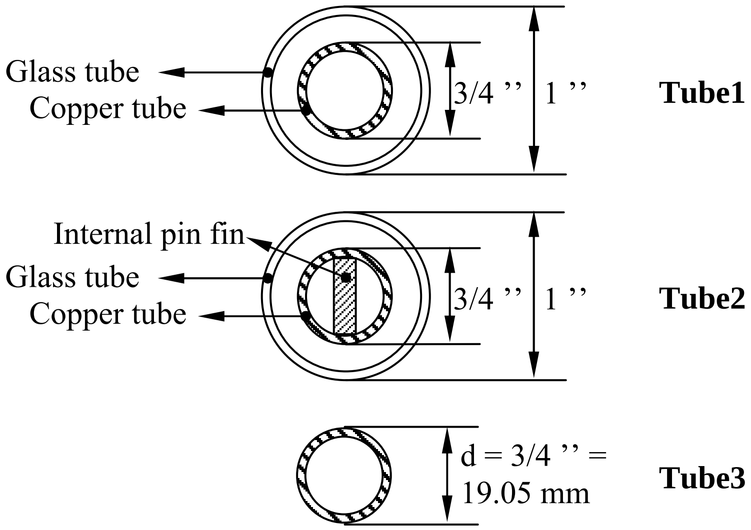

Figure 7. Transversal section of each arrangement for the focal tube

Tube1 promotes a thermal isolation due to the presence of confined air existing between the copper and glass tube, which also exists at arrangement Tube2, as well. Because this annular space, such arrangement still promotes thermal exchanges of radiation and convection to atmosphere, however.

The Tube2 arrangement has internally pin fins of copper, internally welded to the pipe wall, equally spaced along tube length. Such fins have the objective to intensify thermal exchange between tube wall and the core flow, concurrent to increase the turbulence of working fluid as well. The turbulence enhancing aim to promote a better mixing fluid layers, having in mind the low Reynolds numbers at which the system is subjected.

Tube3 is an earlier and basic arrangement which promotes the largest energy loss to atmosphere by convection, because of the non-intensifying thermal exchange between copper tube wall and the working fluid and it is just tested for comparisons reasons.

4. EXPERIMENTAL RESULTS

The experiments were accomplished at three days on march, 2007: 19, 21 and 26 whose atmospheric conditions were similar in respect to weather conditions, aiming the comparison between different tube configurations proposed here. It was considered local external temperature, relative humidity of air, clouds covering and directs solar irradiation levels. For this campaign, Tube1, Tube2 and Tube3 were tested at days 19, 21 and 26, respectively.

During the closed water flow circuit tests, it was fixed a flow of 1.25 ml/s, monitored and controlled by a rotameter. Due to low speed flow, it was became necessary the installation of siphons, one before and another after the focal tube, in order to guarantee its complete fulfillment by water with consequent increase of the thermal exchange between the tube wall and water.

It is important to note that estimation of available instantaneous power is made from global direct solar irradiation on projected mirror area (2 m²) because of the nature of data obtained from the reference source, although this type of solar concentrator does not deal so efficiently with diffuse irradiation as direct irradiation.

Some hourly main data collected in tests ($T1$, $T2$, $\dot{Q}$) and other obtained results are briefly shown in the Tabs. 1, 2 and 3. In these tables, G_I represents the average global irradiated power obtained from the accumulated radiated energy in one hour, informed by Instituto Nacional de Meteorologia – INMET webpage (2007) which keeps an automatic weather station located closed to the experiments site. $\dot{Q}$ is the instantaneous power absorbed by water, calculated by eq. 1. The ratio of $\dot{Q}$ and G_I gives the efficiency η_I,

$$\dot{Q} = \dot{m} \cdot c_P \cdot (T2 - T1) \tag{1}$$

In Eq. (1), $\dot{m}$ is the water mass flow in kg/s, c_P is the specific heat of water at constant pressure in J/kg K. Data marked as G_R means global irradiation value available from the software RADIASOL (2001), which simulate solar irradiation for several Brazilian cities, including Vitória, ES, for any day of year. In order to check data available from

RADIASOL(2001), it is also listed the value ΔG , which represents the percentile error calculated between RADIASOL estimated data value, related to those collected from INMET (2007). The ratio of $\dot{Q}$ and G_R provides the efficiency η_R. RADIASOL (2001) was used with all default parameters, without any configuration adjustment.

Table 1. Experimental and calculated data for 3-19-2007 using Tube1.

Time	T1 (ºC)	T2 (ºC)	$\dot{Q}$ (W)	G_R (W)	η_R (%)	G_I (W)	η_I (%)	ΔG (%)
10:30	32	96	334.3	1402	23.8	1639.4	20.4	14.5
11:00	34	70	188.1	1474	12.8	1742.2	10.8	15.4
11:30	36	72	188.1	1546	12.2	1794.4	10.5	13.8
12:00	38	95	297.8	1618	18.4	1846.7	16.1	12.4
12:30	36	87	266.4	1546	17.2	1857.8	14.3	16.8
13:00	36	77	256.0	1474	17.4	1868.9	13.7	21.1
13:30	34	85	229.8	1402	16.4	1790.0	12.8	21.7

Table 2. Experimental and calculated data for 3-21-2007 using Tube2.

Time	T1 (ºC)	T2 (ºC)	$\dot{Q}$ (W)	G_R (W)	η_R (%)	G_I (W)	η_I (%)	ΔG (%)
11:30	36	79	224.6	1550	14.5	1663.6	13.5	6.8
12:00	35	97	323.9	1622	20.0	1918.9	16.9	15.5
12:30	37	96	308.2	1550	19.9	1925.8	16.0	19.5
13:00	38	96	308.2	1478	9.5	1932.8	16.3	23.5
13:30	37	96	308.2	1406	21.9	1846.4	16.7	23.9
14:00	38	96	303.0	1275	23.8	1760.0	17.2	27.6
14:30	37	97	313.4	1144	27.4	1593.6	19.7	28.2
15:00	32	92	313.4	977	32.1	1427.2	22.0	31.5
15:30	24	78	282.1	810	34.8	1221.7	23.1	33.7
16:00	36	79	219.4	643	34.1	1016.1	21.6	36.7

Table 3. Experimental and calculated data for 3-26-2007 using Tube3

Time	T1 (ºC)	T2 (ºC)	$\dot{Q}$ (W)	G_R (W)	η_R (%)	G_I (W)	η_I (%)	ΔG (%)
09:30	29	63	177.6	1146	15.5	1345.6	13.2	14.8
10:00	31	80	256.0	1280	20.0	1506.7	17.0	15.0
10:30	36	77	214.2	1414	15.1	1653.6	13.0	14.5
11:30	36	54	94.0	1560	6.0	1724.4	5.5	9.5
12:00	36	57	109.7	1633	6.7	1648.3	6.7	0.9
12:30	38	58	104.5	1560	6.7	1694.4	6.2	7.9

Figure 8 show the difference between measured and simulated data, considering INMET (2007) as the most reliable source. As can be see, there is a large variation of such comparison, between 5 and 35%, being average values: 16.5% for Tube1, 24.7% for Tube2 and 11.5% for Tube3, considering the whole time period of measurement.

Although RADIASOL (2001) appears to be an excellent and freeware software, some care is demanded by the user in such way to adjust actual irradiation parameters in order to avoid errors on the analysis. This observation is important to some comparisons and conclusions demonstrated later.

The comparison between the absorption efficiencies obtained by the three different arrangements of focal tubes is better observed in Fig. 9, considering η_I. calculations. It is possible to infer considerable convection heat loss to atmosphere for Tube1 and Tube3 in comparison to the arrangement Tube2, since its design demonstrates larger efficiency during the whole test period, mainly on the interval of time when the irradiation taxes tends to decrease, especially after the period of 13:00.

Such behavior may be explained for Tube 2 pin fins which seem to enhance inner convection. On the other hand, the low flow of water and corresponding small Reynolds numbers tend to keep a laminar and low mixing flow regime reducing the convection coefficient on inner side of focal tube, for Tube1 and Tube3.

Just for comparison aims, the average efficiency gotten by Tube1 is 14.1%, 18.2% for Tube2 and 10.2% for Tube3.

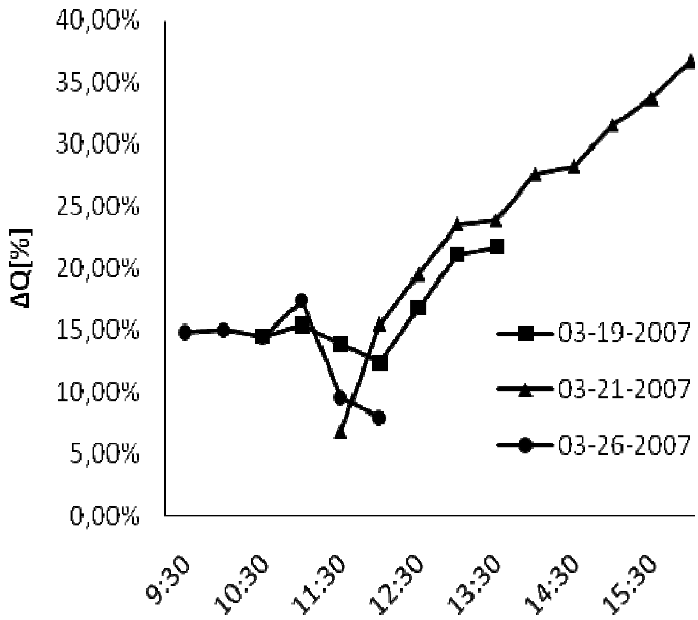

Figure 8 - Comparison between global irradiation data supplied by INMET website and simulated by RADIASOL

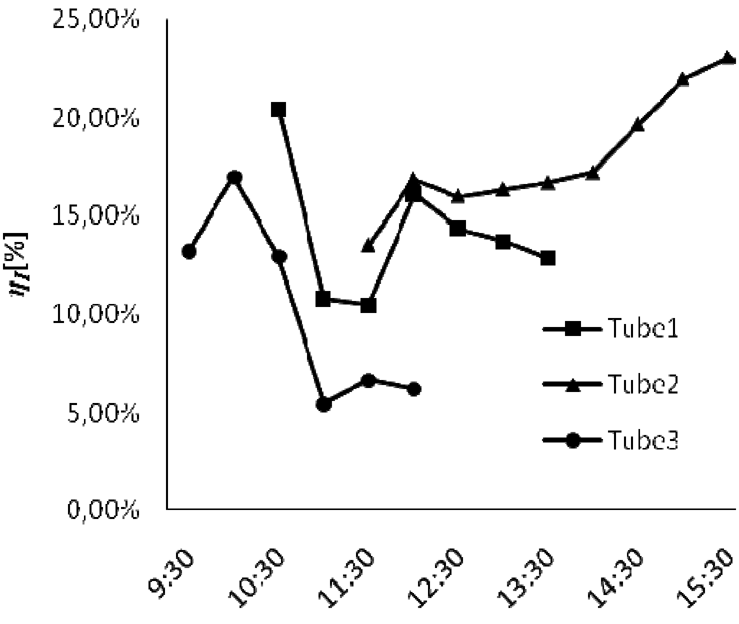

Figure 9 - Efficiency comparison, η_I, among three tube arrangement

The thermal insulation promoted by glass cover tube may be explained analyzing some spectral radiation properties behavior of generic glass, considering Fig. 10. As can be see, major part of glass transmission power occurs between 1.5 to 2.5μm, while 95% of inner copper tube emission, considered here as a black body at 400K, occurs in a wavelength range from 4.5 to 10.5μm, approximately.

So, there is just a little spectral interference between focal tube emission and glass transmission. Actually, 3% averaged emission pass trough glass tube under these conditions. Such insulation phenomenon is usually known as "greenhouse effect".

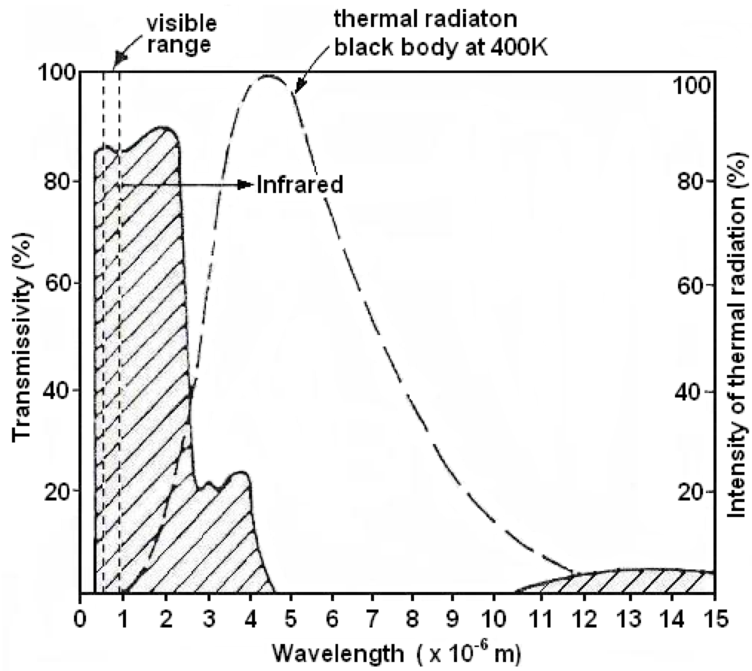

Figure 10 – Spectral dependence of radiation properties for a generic glass (Acioli, 1994)

5. ANALYSIS AND CONCLUSIONS

As expected, the arrangement Tube2 presented the better efficiency, although analysis about Tube1 and Tube3 are do not conclusive at all. The internal pin fins installation really contributes for enhance heat transfer for working fluid flowing inside focal copper tube. Tube2 is elected to be used in next stages of this project.

The low efficiency observed to the whole system (23% max.) maybe is due to a criterion lack in the arrangement assembly. It was noted that parabolic focus was not precise on the tube, presenting an unexpected diffusive component.

Another aspect to be observed is about the data precision generated by RADIASOL (2001) software when compared to irradiation data from INMET weather station, located few meters from the experiment site. Data is collected automatically by station and it will be used as reference data from now, although the measured accumulated irradiation data has to be converted from kJ/m^2 to W/m^2 as used in the present work, generating some error due to this conversion process.

6. FUTURE WORKS

The main objective to project consolidation will happen with the construction of a secondary circuit for oil cycle, just as mentioned in the introduction of this article (it was not shown here because electrical problems occurred with oil pump during initial tests).

Also, it is necessary to study the viability of phase change thermo-accumulation, in order to use parcels of solar heating at night or cloudy periods of day, as proposed in Fig. 2. Of course, this methodology will be justified just after adjustments on parabolic mirror shape in order to get a better focus to promote higher temperatures, as characterized by such parabolic concentrator.

A Nusselt number correlation may be developed, similar to that proposed by Dogruoz, *et al.* (2005) in their article, aiming to optimize the dimensions of pin fin in-line array in relation to internal tube heat transfer.

7. ACKNOWLEDGEMENT

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