Comparison of essential efficiency characteristics of selected vacuum tube solar collectors

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ABSTRACT

The presented paper deals with determination of the basic performance characteristics of solar vacuum tubes, which are in this case represented with thermal efficiency of solar collector and curve of incidence angle modifier. These characteristics are determined for the three types of solar vacuum tubes from different manufacturers. Comparison of efficiency properties of different types of solar collectors helps to analyze the factors affecting these fundamental properties of solar collector. Measuring of the basic operation parameters was carried out on the measuring apparatus developed and manufactured by authors in the Centre of Renewable Energy Sources, Faculty BERG, Technical University of Košice in the various climatic and weather condition. All measurements were made in a quasi dynamic outdoor conditions. As a results of measurements were drawn up series of efficiency curves and incidence angle modifier curves on which basis were considered solar collectors analyzed and evaluated.

Keywords: solar energy, solar vacuum tubes, thermal efficiency, incidence angle modifier,

INTRODUCTION

Renewable energy sources are rapidly developing energy sectors, their use is widespread and can reach many sphere of life [1],[2]. Perfect knowledge of their characteristics allow their use for the best results. [3] Applications in the field of solar energy should be tested in various ways [4],[5] but mostly in form of thermal performance [6] or in form of efficiency or incidence angle modifier. Comparison of efficiency characteristics of different types of solar collectors [7] enables to analyze factors that affecting these, for solar collector fundamental properties. It also allows to assess behavior of the solar collectors in various applications and under various ambient conditions and based on obtained results allows to determine the extent of use of different types of solar collectors in various solar applications (pool heating, year-round domestic hot water heating, space heating or heating in technology process). Correctly identification of the type of solar collector that is suitable for given application fundamentally affects the behavior of entire solar thermal system.

Essential efficiency characteristic of solar collectors

The basic parameters defining characteristic of solar collector in terms of heat production are solar collector efficiency at different climatic conditions and influence of changes in the angle of incidence of solar radiation that affect solar collector efficiency. Solar collector efficiency under various climatic conditions mainly depends on the thermal insulation of solar collector and ability of solar collector to convert solar radiation into the heat and subsequently drains heat to the manifold header where heat transfer medium is flowing. Based on the efficiency of the solar collector under different conditions (intensity of solar radiation I, ambient temperature t_e, absorber temperature t_a) is determined efficiency curve of solar collector acording to the medium reduced temperature gradient $(t_a\text{-}t_e)/I$, which is the fundamental characteristic of the solar collector efficiency. [8] Another important characteristic of the solar collector is the incidence angle modifier that describes the dependence of the solar collector efficiency on the angle of incidence of solar radiation. [9]

Solar collector efficiency

For determination of the solar collector efficiency it is necessary to determine the effectiveness of individual values of effectiveness that corresponding to given climatic conditions. According to [10] is efficiency of solar collector η [-] under steady-state conditions defined as the ratio of heat output dissipated in heat transfer medium to the input of solar radiation reaching the solar collector.

$$\eta = \frac{P}{P_I}$$

where P [W] is output of solar collector and P_I [W] is input of solar radiation on aperture of solar collector. After determination of performance values pertaining to a given weather conditions is possible to plotted on the basis of efficiency curve based on the reduced temperature gradient. Value of medium reduced temperature gradient X [$m^2.K.W^{-1}$] that defines climatic conditions is given by:

$$X = \frac{t_m - t_e}{I}$$

where t_m [°C] is mean temperature of heat transfer medium between inlet and outlet of solar collector, t_e [°C] is ambient temperature and I [$W.m^{-2}$] is solar radiation intensity. [10] Solar collector efficiency, respectively efficiency curve have to be always referred with the reference area of solar collector. The maximum value of efficiency η_0 is the efficiency of the solar collector at zero temperature difference between the heat transfer medium and the surrounding environment, i.e. with maximum limits of heat loss. It express the optical quality of solar collector (glazing transmittance, absorbability of absorber) and also the ability to drain heat from surface of absorber into the heat transfer medium. It is often referred as optical efficiency of the solar collector. [8]

Incidence angle modifier

Abovementioned expression of efficiency or efficiency curve of solar collector is based on the tests of thermal behavior of solar collector under steady state defined conditions - clear sky with significant component of direct sunlight and perpendicular angle of solar radiation incidence on the solar collector plane. However, such a conditions are not part of the standard operation of solar collector, the incidence angle generally varies due to the variable geometry of solar radiation during day and year, and the proportion of direct radiation varies due to the cloudiness. Efficiency curve, respectively performance curve of solar collector is therefore not sufficient for complex assessment of its performance. Efficiency curve must therefore be complemented by depended value that expresses change in efficiency of solar collector with changing incidence angle of solar radiation. This dependence value is the incidence angle modifier K_0 [-], which shows the optical characteristics of solar collector. [11] Incidence angle modifier is defined as the ratio of the optical efficiency under general angle of solar radiation to the optical efficiency under perpendicular angle of solar radiation.

$$K_0 = \frac{\eta_0(\theta)}{\eta_0(0')}$$

Depending on incidence angle is curve of incidence angle modifier experimentally defined in longitudinal (K_{0L}) and lateral (K_{0T}) plane. Flat and optically symmetric solar collectors have two identical curves of incidence angle modifier, the shape of optical characteristic is predictable and in various types of flat plate solar collectors vary in the range of several percent. Therefore, tests determine value of incidence angle modifier only for an angle of 50°. For optically asymmetric solar collector, such as single-wall or double-wall vacuum tube collectors, it is also necessary to determines values for incidence angle modifier for lateral plate. In longitudinal plane has curve of incidence angle modifier of vacuum tube solar collector shape similar to the flat plate collectors. [8] Dependence of the optical effectiveness on incidence angle for various types of solar collector generally differ. Incidence angle modifier allows to take into account the impact of the optical characteristic of the solar collector (shape of aperture, absorber or reflector) on his performance (heat gain) for general geometry (slope, azimuth, angle of incidence) and conditions of solar radiation (direct, diffuse and reflected component of solar radiation). Characteristic of incidence angle modifier is primarily used in computer simulations of the solar system.

METHODOLOGY

The measurement process was carried out at the Centre of Renewable Energy Sources, Technical University of Košice, Slovakia with using of measuring rig designed and manufactured by authors. As a base of measuring apparatus was used data acquisition system KIMO AMI 300 with thermocouple probes KIMO TTKE-363 (type K, range from -40°C to +400°C) and flowmeter SMART +JS-02 (accuracy ±5% F.S.). Intensity of solar radiation was measured with solarimeter KIMO SL100. Within the testing was measured three types of solar vacuum tubes - Veelman VSP15HP (length 2 015 mm, diameter 57.4 mm, type of absorber - cylindrical); Viessmann Vitosol 300-T (length 2 090 mm, diameter 59.8 mm, type of absorber - flat); no-name Chinese solar vacuum tube (length 1 895 mm, diameter 54.7 mm, type of absorber - cylindrical).

For determining the effectiveness of the solar vacuum tube is necessary to measure values that are directly involved to the process of its calculation, these are values to calculation of the amount of energy forwarded by solar vacuum tube and values determining the amount of energy incidence on area of solar vacuum tube: temperature of heat transfer medium at heat exchanger inlet t_1 [°C]; temperature of heat transfer medium at heat exchanger outlet t_2 [°C]; volumetric flow rate of heat transfer medium

Q_v [m^3.s^{-1}]; intensity of solar radiation I [W.m^{-2}]; reference area of solar collector A_k [m^2]; ambient temperature t_e [˚C]; temperature of absorber t_a [˚C] (respectively mean temperature of heat transfer medium t_m) [˚C].

The difference between t_1 and t_2 gives the change in temperature of the heat transfer medium between exchanger inlet and outlet. Measuring of volumetric flow rate of heat transfer medium is necessary for determination of mass flow rate Q_m [kg.s^{-1}], which is obtained by multiplying with density of heat transfer medium. With using these parameters and specific heat capacity of water it is determined the amount of energy forwarded by solar vacuum tube for further demand (i.e. heating). Multiplying the value of solar radiation intensity I [W.m^{-2}] by reference area of tube A_k [m^2] and time period of measurement gives amount of energy incidence on area of solar vacuum tube. As reference area of solar collector was in comparison as most suitable area used area of aperture. In the case of using of absorber area as reference area will be Sydney tube favoring against single walled vacuum tube, that have smaller absorber area than aperture area. Values of t_m, t_e, t_a and I are relevant for determination of reduced temperature gradient X [m^2.K.W^{-1}]. The parameter X determines the position of the vacuum tube efficiency on horizontal axis, i.e. characterize tube efficiency at the corresponding conditions. For the flat plate solar collectors is to determine the value tm using mean temperature of heat transfer medium between the inlet and outlet of collector, which roughly corresponds to the temperature of solar collector absorber and based on its value it is possible to assess the displacement of tube efficiency on horizontal axis due to the changes of heat loss of solar collector caused by difference of absorber temperature and ambient temperature. In presented case, the heat transfer medium did not washed directly solar vacuum tube absorber but flows only through the heat exchanger where are condenser of vacuum tubes inserted, therefore the mean temperature of heat transfer medium does not correspond to temperature of absorber, and its use in calculation of parameter X would significantly distort the results. The solution to this problem is to measure the temperature of the absorber at the outlet of evaporator out of glass tube.

The result of data processing of the measuring is the curve of efficiency based on the reduced temperature gradient for each vacuum tube, and the curve of incidence angle modifier for three types of vacuum tubes with different optical properties.

RESULTS AND DISSCUSSION

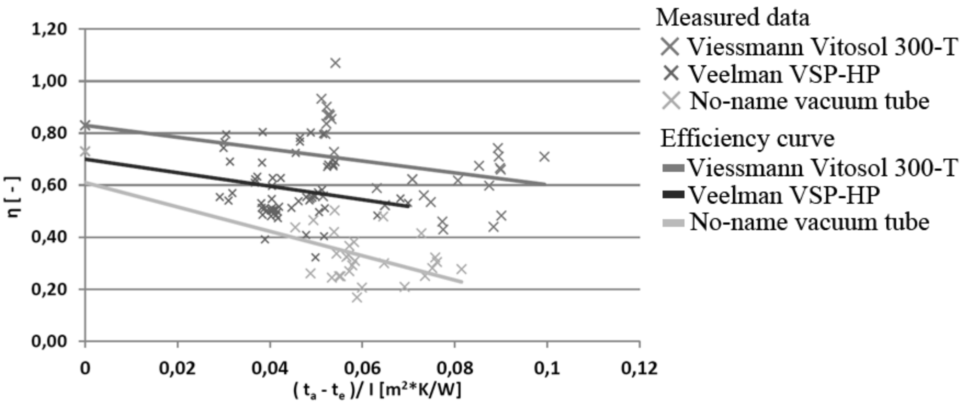

Fig. 1 Efficiency curves of evaluated vacuum tubes

From Fig. 1 can be concluded that effectiveness of each vacuum tube is significant different. Effectiveness of vacuum tube Viessmann Vitosol 300-T can be based on climatic properties characterized by equation $\eta = - 2.282*X + 0.83$. The increase of value X from 0 to 0.05 $m^2.K.W^{-1}$ causes reduction of efficiency about 14% of its maximum value (this situation occurs e.g. when the intensity of the solar radiation decreases about 350 $W.m^{-2}$). Efficiency of Veelman vacuum solar tube should be based on climatic properties characterized by equation $\eta = - 3.258*X + 0.73$. Change of value X from 0 to 0.05 $m^2.K.W^{-1}$ causes reduction of efficiency about 22% of its maximum value. No-name vacuum solar tube from unknown Chinese manufacturer has equation of efficiency in form $\eta = - 4.695*X + 0.61$ and increase of value X from 0 to 0.05 censuses drastic reduction of efficiency about 39% of its maximum value.

Solar vacuum tube Viessmann Vitosol 300 - T achieved highest efficiency from all evaluated vacuum tubes under different weather conditions. Also, the efficiency of this tube decreases with changing weather conditions at least. Lower efficiency demonstrated during measurement vacuum tube Veelman VSP-HP. The percentage difference between efficacy of Veelman vacuum tube and Viessmann vacuum tube is approximately 32% (determined from average *X* parameter in the range of 0 to 0.2 $m^2.K.W^{-1}$). The lowest efficiency reached No-name vacuum solar tube from unknown Chinese manufacturer. Descent characteristics with increasing X (low intensity radiation and low outside temperature) is the steepest of comparison tubes. The percentage difference between efficacy of Viessmann vacuum tube and No-name vacuum solar tube from unknown Chinese manufacturer is approximately 64%, compared to Veelman vacuum tube it is 44% less efficiency.

The results of measuring was presented besides efficiency curve also as the curve of incidence angle modifier presented in Fig. 2. Significant differences of incidence angle modifier are caused by different shape of vacuum tube absorber.

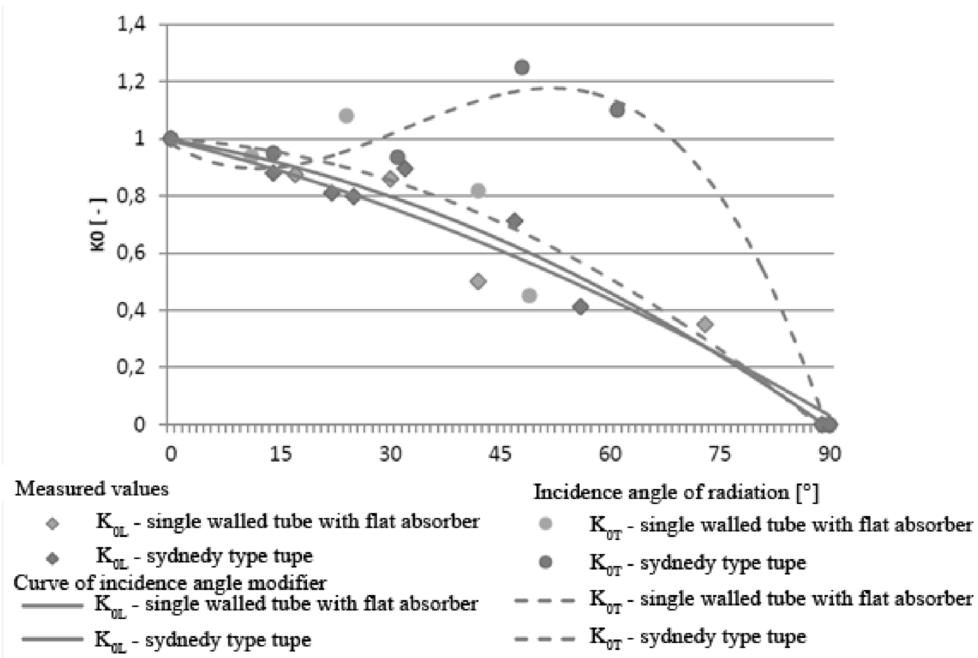

Fig. 2 Curve of incidence angle modifier for evaluated vacuum tubes

As can be observed, changes of incidence angle modifier occurs when azimuth of sun is changing during the day and thus Sydney type vacuum tube have more stable efficiency than vacuum tubes with flat absorber. When summarizing the curves of efficiency and incidence angle modifier, we concluded that the most efficient of the evaluated tube is a vacuum tube Viessmann Vitosol 300-T. The only characteristic where Viessmann Vitosol tube did not achieved best results was curve of incidence angle modifier for lateral plane. Lower efficiency depending on reduced temperature gradient had Veelman VSP-HP vacuum tube and as a vacuum tube with significantly lower efficiency had proven No-name vacuum solar tube from unknown Chinese manufacturer (average values of efficiency reached values comparable to flat plat collectors). It should, however, take into account the fact that sydney types vacuum tube in comparison with Viessmann tube (single walled with flat absorber) showed higher values of K_{0T} at an angle of solar radiation $\gamma > 30^{\circ}$. The above results show the possibility of applying individual tubes in thermal solar systems. Vacuum tube solar collectors with low slope of efficiency curve (high efficiency even under low environment temperatures and low intensity of radiation) - in our case it was Viessmann Vitosol 300-T, are designed for solar systems for water heating or additional heating. Such use is also possible in the tube Veelman VSP-HP, but with lower overall efficiency. No-name vacuum solar tube from unknown Chinese manufacturer is not appropriate for such applications and it is advisable to use it only for water heating applications.

Fig. 2 shows that the optical properties in the longitudinal plane for both designs of the tubes are very similar. So the change in the angle of incidence of solar radiation that arises due to changes in the height of the sun above the horizon during the day and the year, will not cause significant differences in the effectiveness of different types of tube collectors. Significant differences between values K_0 for all vacuum tubes were observed in the lateral plane. For single walled vacuum tube was steady decline of K_{0L} with increasing value of the angle of incidence of solar radiation. Sydney types of vacuum tube responded by gradually rising the K_{0L} with peaks at $\gamma = 40 – 60^{\circ}$.

The results showed significant differences in performance characteristics of individual vacuum tubes. These differences are due to the type design and the level of workmanship. High efficiency of Viessmann Vitosol 300-T is caused by an effective solution to heat transfer from the absorber to the heat pipe evaporator. Solar radiation that incident absorber of vacuum tube is converted into heat and it is directly drained to the evaporator of the heat pipe. Surface finishing of absorber is formed by a coating which provides enhanced photothermal conversion of radiation. For sydney types of tubes (Veelman VSP-HP, No-name vacuum solar tube from unknown Chinese manufacturer) converted heat passes through inner wall of double glazing and then by aluminum absorber to the evaporator of the heat pipe. Contact between the glass wall, aluminum absorber and evaporator is maintained by flexibility aluminum fins. Heat transfer between the contact surfaces of absorber fins and evaporator heat pipe with such a contact is significantly worse compared to that of the tube Viessmann Vitosol 300-T. Heat transfer between absorber and evaporator of heat pipe is for sydney type tube worse because of fact, that heat passes through more components of tube, e.g.

through the inner glass tube and aluminum fins (with considerably larger dimensions than that of the Viessmann tube). Also thermal conductivity of these components is for sydney types of tubes significantly lower (thermal conductivity of glass k = 1,05 $W.m^{-1}.K^{-1}$, aluminum k = 250 $W.m^{-1}.K^{-1}$) than for single walled tube like Viessmann tube (thermal conductivity of copper k = 401 $W.m^{-1}.K^{-1}$).

Low-lying curve of efficacy in sydney tubes also cause worse insulate of individual vacuum tube components what causing an increase in heat loss. For sydney tubes is by vacuum insulated only absorber itself, while after passage of heat through the glass inner tube are its loss limited only with piece of insulating material inserted into the glass tube. For Viessmann vacuum tube are all of the components insulated by vacuum, except the condenser that is plugs into the insulated manifold header of solar collector. Another reason why tube Viessmann achieves higher efficiency is the ratio of the aperture area to the absorber tube in tube Viessmann where the ratio is about 0.9 in sydney tube this ratio is at about 0.79. This fact caused situations when the tubes are incident by the same amount of energy, but the energy that absorber receives depends on the aforementioned ratio.

When comparing structural differences between the Veelman VSP-HP tube and the No-name vacuum solar tube from unknown Chinese manufacturer was clearly observable lower precision of no-name tube, which is reflected in the design of thermal contact between the absorber, evaporator plate and heat pipe. With absorber and evaporator was possible to effortlessly move, what suggesting a very imperfect design of that contact. It was also worse insulated space between the inside of the tube and external environment. These structural imperfections caused deterioration of the heat transfer between surfaces of the absorber and evaporator and increasing heat loss, which results in a lower-laying characteristic of efficiency curve for no-name vacuum tube considerably higher value of its directive.

Comparing the impact of design solutions for incidence angle modifier is clearly noticeable advantage of cylindrically shaped absorber of sydeny types tubes, which results in better characteristics K_{0T}. When changing the angle of incidence in the transverse plane sydney tube exposes larger area to solar radiation than the single walled tube with flat absorber which explains the shape of the curves IAM these tubes in the transverse plane. Compared to single-walled tubes with flat absorber sydney tube conception showed higher values of K_{0T} at an angle of solar radiation $\gamma > 30^{\circ}$. Situation where sydney tubes have a higher value than single walled tube with flat absorber occurs for more than 60% of the year. When determining the characteristics for the entire collector, however, due to the mutual shielding of individual tube is this characteristic for sydney tubes partially worse.

CONCLUSION

Determined characteristics in form of curves of efficiency and curves of incidence angle modifier clearly describes the performance of three types of evaluated vacuum tubes. Measurement was performed on measuring apparatus that was designed and manufactured by authors at Centre of Renewable Energy Sources. Presented results adequately compare the essential operation parameters of measured tubes. The results illustrate the advantages and disadvantages of different designs of vacuum tubes and highlight the importance of the quality of construction and the way of heat transfer in a vacuum tube. In a substantial part describes the impact of the shape of the absorber on efficiency vacuum tubes. Identified characteristics suggest structurally best solution of vacuum tube collector which is single walled vacuum tube with cylindrical metal absorber. This design combines the benefits of incidence angle modifier of sydney type tube characteristics with the benefits of the efficiency curves of single-walled vacuum tube collectors.

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