DESIGN OF VACUUM THERMAL INSULATION FITTING IN SOLAR HEATING APPLICATIONS

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Abstract:

The presented paper deals with designs of the vacuum thermal insulation fitting in solar heating applications. Fitting designs, identified by the authors of this paper, reflects the construction problem of a flat vacuum solar collector caused by the conduction of heat gained with solar collectors to the collector casing through thermal conductive connection located across the interface between casing and outer piping. As this heat further leaks into the surrounding environment, heat losses of the solar collector is higher and therefore thermal performance of the whole solar system is reduced. The solar collector element in the form of a vacuum thermal insulation fitting allows a connection of the solar collector with outer hydraulic circuit of the solar system without creating thermal bridges while ensuring vacuum tightness of the collector casing. A part in the evaluation process of the proposed design was a vacuum thermal insulation fitting modelled in CAD environment followed by heat transfer analysis under several operation scenarios (normal operation, extreme operation, etc.). Subsequently, a functional prototype was manufactured for measurements and verifications of the desired characteristics of fitting under different operating conditions. All the results of measurements and simulations demonstrated not only the ability of fitting to ensure vacuum tightness of the solar collector but also the ability of reducing overheating of the collector casing as well.

1 Introduction

Solar heating applications in form of the flat plate or tube solar collector have been widely used in various fields of the human activity. The collector types differ substantially not only by structural parts but also by the philosophy of the conversion of solar energy into usable heat. Also, they differ by thermal insulation which is usually created with thermal insulating blocks of a suitable material or

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with a vacuum in the body of the solar collector, which reduces the heat loss. Flat vacuum solar collectors that use vacuum as a thermal insulation make connection between conventional flat solar collectors and vacuum tube solar collectors, the construction of which is relatively complicated. There are currently various amounts of flat vacuum solar collector designs. Design published in patent CN102128498 [1] is often used by manufacturers. This vacuum eliminates heat losses from the frontal part of the solar collector through transparent cover. In this design, collector piping of the heat transfer medium is routed out form the collector casing in the conventional thermal and non-conductive way, because the connection does not have to ensure vacuum tightness of the whole collector casing. Another design describing a flat vacuum solar collector is published in WO2008013439 [2]; However, in this specification, the vacuum chambers are made similar to vacuum tube solar collectors, which increases a demand on manufacturing. Design presented in US4881521 [3] enables the creation of vacuum thermal insulation in the space around the absorber in a way that allows maintaining the vacuum longer, which significantly increases the operation parameters of solar heating system. Specific designs of solar collectors allow implementation of innovative solutions in the wide range of their construction parts.

The presented paper is dedicated to the construction of vacuum flat plate solar collector with design published in US4881521 [3] in form of vacuum thermal insulation fitting. Fitting design may also find use in other applications (from non-renewable energy sources) that required both vacuum tightness and thermal insulation. Although vacuum flat plate solar collector design presented in this paper has been applied in the industrial production for many years, it still exhibits several deficiencies that deteriorate operation parameters of the solar heating system. They have been consequently identified by the authors of this study in the field of heat losses. According to results published in [4],[5],[6],[7], heat losses of the vacuum flat plate solar collector eliminated by a process of reducing the transfer of heat by convection and conduction in the air gap at the front of the absorber without reducing the optical efficiency of the collector. Thus, the only significant source of heat losses from the collector casing is the presence of thermally conductive connection which conducts heat from heat transfer fluid pipes and connecting pipes to the surface of the collector casing. These heat losses can be compensated for through design innovations described by the authors of this paper, respectively through presented solutions published in JP2003021404a [8] and JP56010653 [9], which, however, do not reflect all the operating conditions of solar collectors.

2 Design of the vacuum thermal insulation fitting

The fundamental task during designing of vacuum thermal insulation fitting was to find an inner configuration of fitting from the point of dimensions, geometry and material composition, which would ensure the vacuum tightness of the collector casing even under extreme operating conditions such as high temperature that may cause the changes in dimensions of structural components of the solar collector (temperature dilatation).

It was necessary to incorporate a thermal contact element into the fitting, forming thus the thermal bridge break at the interface between piping and collector casing. Due to the large thermal stress of the interconnection, approximately of 220 °C [10], it was necessary to separate the element with the thermal insulation function from that of thermal expansion. The proposal itself ensured the ease of construction while, at the same time, maintaining the required functions. An optimal design of vacuum thermal insulation fitting has three main structural parts: metal body of fitting, blocks with thermal insulation function and elastic compensation elements ensuring vacuum tightness. A body of fitting made of brass serves as a support portion for the whole structural element in terms of mechanical stress or strain. Its secondary function is to connect blocks of the thermal insulation material and copper piping of solar system. Blocks of thermal insulation materials could be made of flexible elastomeric foam, polyurethane, various ceramics or polypropylene. Elastic compensations element ensuring vacuum tightness of collector casing could be made of material based on silicone (synthetic rubber) in the shape of O-rings.

We managed to create such a layout of fitting that only the vacuum seal on the contact of collector casing and thermal block is stressed at high temperatures. The design of vacuum thermal insulation fitting is granted as a patent SK286527 by Industrial Property Office of Slovak Republic [11] and was presented in limited form as a technical brief in [12]. The vacuum thermal insulation fittings, shown in Fig. 1, correspond to patent specification in two examples of embodiments and two positions regarding the interior of the solar collector, where 1 - brass frame, 2, 3 - plastic thermal insulation blocks, 4 - expansion-compensating seals from silicone O-ring, 5 - washer, 6 - mat, 7 - solar collector piping, 8 - layer of sealant.

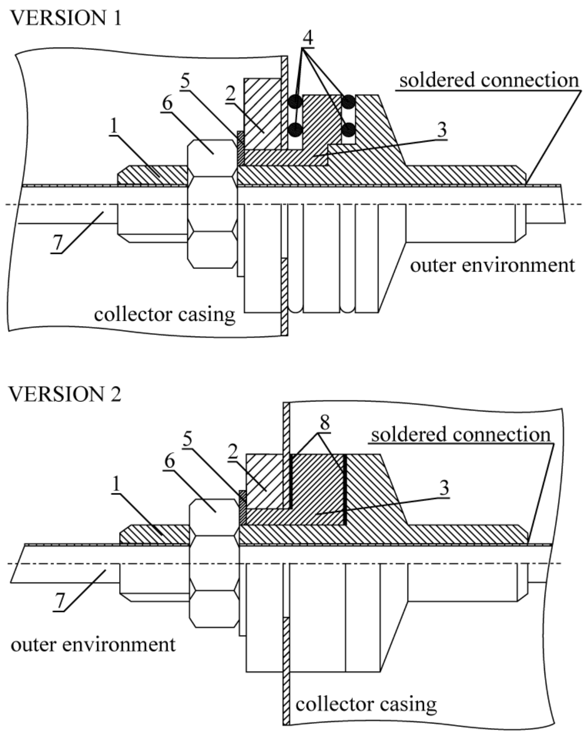

Figure 1. Design of vacuum insulation fitting in two versions - with silicone O-rings, and the layer of sealant.

While the original copper tube is passing through the interior of the brass fitting - frame fitting, it is soldered all around at one end.

3 Methodology

The identification of the presence of heat transfer from the collector and its connecting pipes to the surface of the collector casing was carried out in situ. On the back of the collector casing there were locations identified with a significantly higher temperature than that on the other collectors of different designs, but of a similar composition. Since the connecting pipes to the collector were thoroughly insulated with thermal insulation blocks, the heat source - conductive heat transfer in pipes via all four corners of the collector casing was identified only after the insulation had been removed.

In the first phase of the evaluation process, heat transfer was analyzed with application of a widely used and accepted computational finite element method [13]. Original gland sealing and newly designed fitting in version no. 2 were modelled in CAD software Ansys Design Modeller. Each model consists of fitting, respectively gland sealing, copper piping and substitution of collector casing. Discretized CAD models with 221 000 cells created an unstructured computational network. All component materials were defined by density, specific heat and thermal conductivity according to material library. Each material property was separately assigned to each part of the model. Small simplification of parts, e.g. chamfer or thread, was carried out due to the optimization of computational time and PC hardware requirements. Simplification of geometry lies only in the fact that the thread of the bolts (flanges) and the nuts are not drawn. Bolts (flanges) and nuts do not touch a thread but a flat surface.

The purpose of this analysis was to describe heat transfer from solar collector piping to the collector casing. Heat transfer analyses were performed with proposed vacuum thermal insulation fitting and also with original gland sealing system. Simulations were also aimed at determining the temperature of individual parts of the fitting during the so-called "stagnation condition of the collector" in order to determine whether the proposed construction material is potentially capable of withstanding the thermal stress. Stagnation conditions of the solar collector occur when the heat transfer fluid does not circulate in the collector due to high temperature absorber and because the heat removal from the collector is discontinued. This condition is referred to as "the stagnation state" and the temperature of the collector’s absorber in this state is called "the stagnation temperature" [14], [15]. The value of the stagnation temperature can be considered as the maximum temperature of the collector. The calculated stagnation temperature for the Central European person, according to the energy balance equation [16], amounts to 306 °C. We consider perfect vacuum inside of the collector casing so that the simulation parameters are set so as to completely eliminate heat transfer inside the collector casing. As the purpose of simulation is to study heat transfer in the solid materials, there is no need to use a turbulence model for fluid flow; we can, therefore, consider a laminar flow [17]. Simulations were carried out using Ansys 13 Fluent computational code. Also, SIMPLE scheme and second-order discretization were used as concepts for computational algorithms. The numeric modelling of heat processes in the examined object results from the equation (1):

$$\frac{\partial}{\partial t}(\rho E)+\nabla(\vec{v}(\rho E+p))=\nabla.\left(k_{eff}.\nabla T-\sum_{j}h_j\vec{J}_J+(\vec{\tau}_{eff}.\vec{v})\right)+S_h, \quad (1)$$

where, k_{eff} is the effective conductivity ($k_{eff}= k+k_t$, k is thermal conductivity and k_t is the turbulent thermal conductivity defined according to the turbulence model being used) and $\vec{J}_j$ is the diffusion flux of species j. The three parts on the right side of the equation represent the heat transfer by conduction, diffusion and viscous dissipation. S_h represents heat from the chemical reaction and other defined heat sources. In the given equation,

$$E=h-\frac{p}{\rho}+\frac{v^2}{2}, \quad (2)$$

where, for incompressible flow h is defined as,

$$h=\sum_j Y_j h_j+\frac{p}{\rho}, \quad (3)$$

Y_j is the mass fraction of j, and h_j is defined as,

$$h_j=\int_{Tref}^{T}c_{p,j}dT, \quad (4)$$

T_{ref} is the initial reference temperature. In the rigid structures, the energy conduction has the following form [18]:

$$\frac{\partial}{\partial t}(\rho h)+\nabla.(\vec{v}\rho h)=\nabla.(k\nabla T)+S_h, \quad (5)$$

where, ρ is density, h enthalpy, k conductivity, T temperature, and S_h volume heat source. Eq. 5 expresses the heat dissipation in solid phases, where $k_{eff} = k$, without k_t because it is affected by the selected turbulence model. Besides, it only makes sense for the fluid flow.

We refer to the flowing three of all conducted simulations, where boundary conditions are used in accordance with normal, respectively, stagnation state of the solar collector:

1. Original gland, media temperature of 40 °C, temperature of the outer surface of -10 °C, flow rate of 0.1 $m.s^{-1}$;
2. Designed fitting, media temperature of 40 °C, temperature of the outer surface of -10 °C, flow rate of 0.1 $m.s^{-1}$;
3. Designed fitting, media temperature of 306 °C, outer surface temperature of 30 °C, flow rate of 0 $m.s^{-1}$.

After computational heat transfer analysis, the construction phase started and then two prototypes were constructed. For the experimental verification of the proposed functions of the vacuum thermal insulation fitting, hermetically sealed vacuum chamber (see Fig. 2) was constructed, from which the vacuum pump drained the air to the value of the residual pressure of 6 kPa. The experimental chamber enables the flow of heat transfer media to be conducted at the desired temperature through copper pipes similar like the solar collector. Two thermal vacuum insulation fittings were installed in the vacuum chamber after its completion. The front parts of the vacuum chamber are made of lightweight and structurally strong [19] Al-Mg sheet plates representing the walls of the collector casing. In order to check pressure conditions inside the vacuum chamber and evacuate the area of the chambers, the chamber is equipped with a vacuum adapter. The device has been used to carry out experiments with the following aims. First, it has to verify the tolerance of the fitting in terms of maintaining vacuum tightness in case of a step change in temperature, occurring mainly during the intermittent operation of the solar system in a low temperature environment (stress tests). Second, it has to verify the performance of thermal insulation features of the fitting. In the experiment aimed to verify the vacuum tightness, the experimental chamber was located in an environment of temperature -10 °C. The empty copper pipe was filled with hot water with the purpose of filling the entire volume of the pipe. At the end of each measurement, hot water was drained and the experimental chamber cooled down. Hot water temperatures varied at 98.9, 60 and 40 °C and measurement was executed in three series.

Figure 2. Experimental vacuum chamber during measurements.

The experiment aimed at verifying the performance of thermal insulation features of the fitting consisted of measuring the temperature of both fitting's brass frame and chamber's Al-Mg front at the point where the tubes went through the front of the chamber. The experimental chamber was connected with hot water inlet at the temperature of 40 °C and mass flow rate of 0.002 $kg.s^{-1}$. The temperature at selected points located on the solar collector casing was measured using thermometer TESTO 860 with JTC-K thermocouple probe, and calculated total uncertainty amounts to ± 1.5 %.

4 Results and discussion

Requirements of vacuum thermal insulation fitting in form of vacuum tightness of the collector casing were met and the importance of eliminating thermal bridges was studied by means of physical experiments and computational heat transfer analysis of fitting insulation.

The results of heat transfer analysis of original gland and fitting proposed by the authors are presented in form of temperature maps and graphs that depict the surface temperature of the components. In conducted analysis, water flow in the copper pipe was used as a heat source, which is analogous to the normal operation conditions of the solar collector. Fig. 3 depicts temperature map displaying temperature of proposed fitting during the stagnation condition of the solar collector, i.e. during maximum operation temperature of the solar collector. The longitudinal section view of the temperature map shows an obvious fact that even this extreme temperature does not produce any significant thermal bridges between fitting and collector casing.

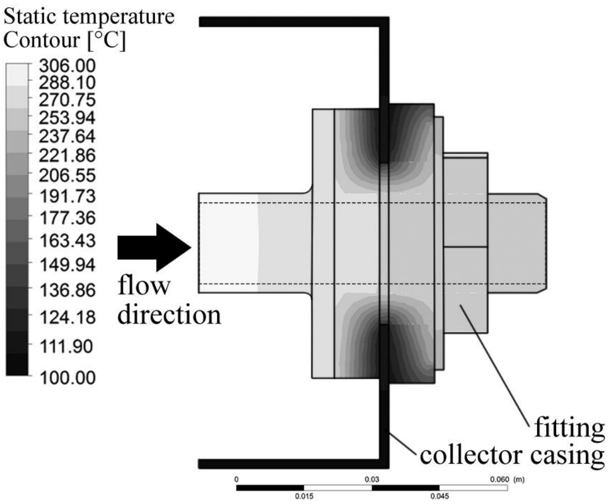

Figure 3. Temperature map in the plane of longitudinal cut in the fitting at the stagnation state of the solar collector.

Fig. 4 depicts a graph showing temperature change of the original gland and proposed fitting depending on the distance from the centre of copper piping with heat transfer medium.

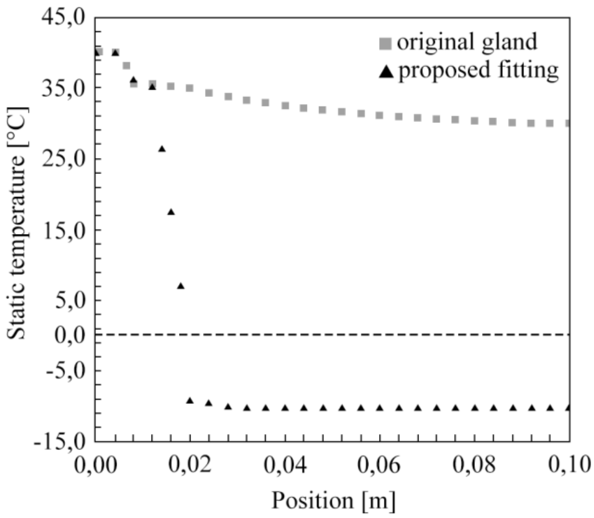

Figure 4. The course of heat distribution from copper pipes to Al-Mg collector casing using the original gland (a) and proposed thermal insulation fitting (b).

In a suitable way, the comparison points out a significant reduction /decrease in temperature of collector casing. Results of physical experiments aimed at testing vacuum tightness during sudden and significant temperature changes demonstrated the ability of fitting to compensate for thermal expansion of its parts through elastic compensation and consequently to ensure vacuum tightness of the collector casing. During experiments, fittings were exposed to high temperature that did not cause any degradation of used materials or changes in dimensions of fitting. According to these results, we can conclude that fitting is able to ensure vacuum tightness of the collector casing.

Table 1 illustrates the data recorded in the second experiment aimed at detecting thermal insulation features of the fitting, i.e. the ability to interrupt the thermal bridges from the piping to the collector casing. Duration of the experiment was 100 minutes. At the quasi-constant temperature of water and ambient air, the temperature of the Al-Mg sheet plates was stabilized after about 30 minutes at -2.7 °C. However, the temperature of the brass shell of the fitting was stabilized after about 90 minutes at 39.0 °C.

Table 1. Results of temperature measurements of the brass-frame fitting and the Al-Mg sheet plates of experimental vacuum chamber

Time	Temperature of air	Temperature of Al-Mg plate	Temperature of brass tubing
min	°C	°C	°C
0	-10.1	-5.1	-5.1
10	-10.0	-3.9	6.9
20	-10.0	-2.9	20.3
30	-10.3	-2.7	31.3
40	-11.1	-2.7	36.8
50	-10.2	-2.7	38.1
60	-10.0	-2.7	38.6
70	-10.1	-2.7	38.9
80	-10.0	-2.7	38.9
90	-10.1	-2.7	39.0
100	-10.0	-2.7	39.0

In addressing the Cu piping transition through the Al-Mg collector casing, instead of using the original gland element that only fulfilled the function of vacuum insulation, a fitting element was proposed, the arrangement of which was conditioned by achieving an interruption in the thermally conductive connection. Already in the first stage of the experimental verification of the newly designed fitting features, i.e. during “stress tests” approach for testing vacuum tightness, it was obvious that the heat from the copper pipe was transferred onto the brass skeleton of the fitting (which was massive on the prototype), but further thermal conduction onto the Al-Mg vacuum casing front representing the collector casing was significantly limited by the thermal insulation blocks. Since the value of the residual pressure indicated on the vacuum adapter had not changed during the experiment, the ability of the vacuum insulation seal to compensate for sudden changes in the dimensions of individual parts and to compensate for subsequent shifts between them, resulting from the step change in their temperature ranges from Δt 50 to 110 °C, was demonstrated.

During the operation of a solar collector, such step changes occur only in the cases of starting up the circulating pump, after a power failure during the insulation of the solar collectors. The heat shock caused by hot water entering the empty Cu pipe with a temperature of -10 °C results in dynamic changes. Based on the above mentioned fact, it is therefore possible to conclude that the ability of the thermal insulation fitting to provide vacuum tightness in conditions beyond the potentially possible states has been demonstrated. The thermal insulation function was demonstrated during the experiment, when the environment temperature was of -10 °C and constant flow of water with 40 °C was 0.002 $l.s^{-1}$. Hot water was fed into the Cu pipeline passing through the vacuum chamber with a pair of fitting installed in it; After stabilizing and thus reaching stationary process conditions, the temperature of the Al-Mg chamber front at the interface with the fitting was at -2.7 °C. The surface temperature of the copper pipe in the transition point was ranged from 38.9 to 39 °C. The achieved drop of 41.6 to 41.7 °C in terms of the difference between the outside temperature and the temperature of the Cu pipe of 49 °C demonstrates the successful interruption of the thermally conductive connection.

Although the experimental verification showed that the water flow from copper pipe through the collector casing without heat losses had been achieved, only thanks to the computer simulation distribution of heat in the construction group could it be described in detail and comparisons of the original and new solutions under the same conditions could be made. The course of temperature in relation to the distance from the Cu pipe axis, shown in Fig. 4, indicates, after a small step change in the connection of Cu pipe – brass screw joint, an obvious gradual temperature decrease in the Al-Mg plate related to the increase in the distance from the brass screw joint. If we follow the course of temperature in a one dimensional setting, only in relation to the distance from the Cu line axis (ignoring the variability of distance of individual elements from the Al-Mg sheet surface), then at the distance of 20 mm from the pipe axis, and at the contact with the screw joint, the Al-Mg sheet temperature is 34.9 °C, which represents a decrease in comparison to the copper pipe temperature of only 5.1 °C. If the thermally conductive connection between the Cu pipe and the brass screw joint is not a problem in terms of additional insulation by properly shaped and fixed thermal insulation blocks, then it is the heat transfer onto the Al-Mg sheet (vacuum chamber front/collector casing front) that is basically impossible to eliminate by additional thermal insulation. The collector casing, the area of which is slightly larger than 2 m^2, serves as a heat exchanger draining heat acquired by the collector into the environment, which is in conflict with the reason for implementing vacuum insulation of solar collectors – reduction of heat losses.

Using the fitting (see Fig. 4), a reduction in the surface temperature can be achieved at a distance of 20 mm from the Cu pipe axis to the value of -8.9 °C, which is by 48.9 °C less than the temperature of the copper pipe. The difference, when compared to the original solution, is 43.8 °C. A further drop in the Al-Mg sheet temperature takes place gradually at 12.7 mm down to the temperature level of the surrounding environment. In comparison with it, in the original solution at the distance of 100 mm from the axis it is 29.9 °C. Since the value of the heat flux, which was adversely discharged from the collector casing to the ambient air, depends on the temperature gradient, the importance of reducing the surface temperature of the Al-Mg collector casing by applying vacuum thermal insulation fittings on all four connecting lines of the collector is indisputable.

The simulation aimed to determine the distribution of temperature field in the individual parts of the fitting, and the visualized output shown in Fig. 3, has brought along important information about the temperatures in the most stressed place due to an increase in temperature while the collector is in its stagnation stage. In the simulation, the temperature of the heat source and the absorber of 306 °C were considered, which results from the equation of the thermal equilibrium. The most stressed vacuum insulation seal fitted to the extended ring of the fitting brass skeleton is exposed to the temperature of 265 °C.

Since the high temperature resistant silicone was used as a sealant, we assume that the seal and the fitting are able to sustain even these extreme operating conditions. It is necessary to add that the manufacturer of the vacuum solar collector declares 219 °C as the maximum temperature which the collector can achieve. This value, given the vacuum insulation of the collector, is considered to be underpowered; on the other hand, however, this low temperature may be the result of unwanted heat loss at the collector pipe outlet. As the newly designed vacuum thermal insulation fitting reduces heat loss, it was necessary to consider the maximum value of stagnation temperature at 306 °C in the calculations. When choosing the insulation block material, it is also necessary to take into account its ability to withstand temperatures around 265 °C.

5 Conclusion

Since the solar heating applications in form of vacuum solar collectors are designed for high-temperature applications or applications in low-temperature environment, it seems that the identified heat losses suppress the primary advantage of vacuum insulation – reduction of heat losses of the solar collector. By constantly lowering prices of vacuum tube collectors and making them more accessible on the market, this significant deficiency may be rendered important. The vacuum thermal insulation fitting eliminates the identified deficiencies, namely, undesired heat transfer from the collector piping to collector casing. The appropriate combination of structural parts in form of the body, insulating blocks and elastic compensation blocks enables the simultaneous elimination of thermal bridges and ensures the vacuum tightness of the solar collector. Performed computational heat transfer analysis, conducted measurements and installation of fitting to test the experimental chamber confirm the desirable properties of fitting. The construction arrangement of fitting allows maintaining vacuum tightness through its elastic compensation even during extreme operation condition characterized by high temperature and thus thermal dilatation of the solar collector. Fitting design can be further modified in terms of weight and size reduction. Fitting proposed by the authors of this paper solves significant deficiency of the solar collector, but it is also worth mentioning that its use is not limited only to the field of solar collectors or renewable energy sources. The application of fitting can be found in every area where it is necessary to provide simultaneous vacuum tightness as well as thermal insulation by eliminating thermal bridges. Vacuum thermal isolation fitting is protected by Industrial Property Office of Slovak Republic by patent SK286527 [11].

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