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Review

On the efficacy of a proposed unsteady state heat loading protocol

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ABSTRACT

The paper relates to the thermodynamics of heat transfer processes in which the source of heat is a hot gaseous fluid. The effect of systematically introducing alternating conditions of compression and decompression inside a heat exchanger is investigated. The said alternating conditions are actuated by introducing two periodic valves at the heat exchanger inlet and outlet. This unsteady state mode of operation is shown to result in enhanced heat exchange under certain conditions. This method of heat exchange has been termed 'Unsteady State Heat Loading Protocol (USHLP).' Experiments were carried out to compare steady state and USHLP based heat transfer in the context of steam providing heat to a water evaporation process. In the experiments, heat was transferred from steam to an evaporation process through a jacket type heat exchanger. An increase in efficiency of around 42% was observed from replacing steady state heat transfer with USHLP under the same operating conditions and geometric configuration. The results of the experiments are discussed in the concluding sections of the paper. It was noted that consistently less steam was used per unit amount of water evaporated in experiments where USHLP was used as compared to steady state heat transfer.

Keywords: Steady state, unsteady state, heat transfer, periodic valves, compression, decompression.

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INTRODUCTION

The use of heat exchangers to facilitate heat transfer between different mediums is an established practice. The research work that is presented in this paper is motivated by the need to optimize heat exchanger performance. Heat exchanger optimization carries both environmental and economic impetus. Several approaches to heat exchanger optimization have been described in literature. For example, Caputo et al. (2011) describe an optimization method based on the minimization of the life-cycle cost. The method allows the joint optimization of both the equipment design and the cleaning policy. In the same paper, the authors point out that there are basically two different approaches as far as heat exchanger optimization is concerned. The first approach is aimed at the optimal sizing of the heat exchanger usually based on a cost minimization goal, considering capital investment and energy related expenses, or on the maximization of some thermal performance. The second approach assumes that the heat exchanger has been already built and that a maintenance schedule has to be optimized in order to minimize maintenance and energy related costs while satisfying the required heat duty. Yao (2018) reviews the subject of industrial heat exchanger optimization. Yao's paper takes a mathematical approach to heat exchanger optimization. The paper is based on an optimal algorithm with different objective functions. One of the objective functions that are analysed is entropy production. Entropy minimisation is analysed in the context of a network of heat exchangers. Stewart (nd) pays particular attention to finned tube heat exchangers. The paper relates to a design optimization methodology that is described as being applicable to general heat exchanger optimization. It is also shown in the same paper that the proposed optimum design is consistent with minimum entropy generation for the total system.

Turgut (2019) presents a study that utilizes Global Best Algorithm (GBEST) in order to optimize the system parameters of a shell and tube heat exchanger with an aim to obtain its total minimum cost as well as to attain maximum average overall heat transfer coefficient in a separate and simultaneous manner. A lucid genetic algorithm approach to heat exchanger optimization is also presented in Saleh (2012). The paper presents an optimization approach which can be used to obtain optimum plate heat exchanger designs based on single phase liquid. The authors develop Kriging metamodels for the heat transfer coefficient and pressure drop per unit length in a given plate heat exchanger.

In a more recent paper, Krzywanski (2019) presents an artificial intelligence approach to heat exchanger optimization. The paper studies a large falling film evaporator with the aim of comparing a broad range of operating conditions and geometric configurations. Genetic algorithms and artificial neural networks are shown to be applicable in the analysis and optimization of the falling film evaporator. The paper proffers that artificial intelligence inspired analytical techniques can provide a robust and economic framework for heat exchanger optimization.

In a conference paper, Faes et al. (2019) discuss heat exchanger optimization in the context of highly corrosive mediums. This is of interest as corrosive mediums require high material thickness which naturally compromises heat transfer efficiency. Faes et al. (2019) explore an optimal design solution which is based on performing data analysis on various design parameters and estimated lifetime maintenance costs of a heat exchanger. The emergence of Organic Rankine Cycles (ORCs) has motivated considerable research into heat exchanger optimization. Reddy and Thimmasandra (2018), use the Kinetic Gas Molecule Optimization (KMGO) to optimise a shell and tube heat exchanger in an ORC setup. This optimization is achieved due to the fact that the KMGO technique identifies the global minima effectively due to the kinetic gas molecules theory. The KMGO technique is based on the swarm behavior of gas molecules, which is used to provide the criteria for optimization.

From the literature surveyed, the subject of heat exchanger optimization is to a large extent centred on the application of sophisticated optimization algorithms. These algorithms tend to be developed with the objective function being a key parameter such as entropy. The present work introduces an optimization method based on the time evolution of pressure, temperature and molar volume in the heat exchanger volume. We define here the heat exchanger volume as the volume of the heat exchanger unit that provides passage to a hot gaseous fluid as it transfers heat to the medium to be heated.

The central idea that we explore, is the effect of introducing two periodic valves to enact alternating states of compression and decompression in the heat exchanger volume. The two periodic valves are introduced at the heat exchanger inlet and outlet. Compression is achieved by opening the valve at the heat exchanger volume inlet, to allow for passage of the hot gas into the heat exchanger, whilst the valve at the outlet is closed. On the other hand decompression is achieved by opening the valve at the heat exchanger volume outlet, to allow for discharge of the less hot gas out of the heat exchanger, whilst the valve at the inlet is closed. The motivation for opting for this unsteady state method of heat transfer is based on the correlation between temperature and pressure as expressed in standard equations of state. That is, intermittently pressurizing the heat exchanger volume can be applied in periodically raising the temperature of the hot gaseous fluid in the heat exchanger volume. The overall aim of this mode of operation is to achieve a temperature profile in the heat exchanger volume that averages out to a higher temperature compared to what would have been otherwise achieved under steady state conditions.

Theoretical model

A descriptive theoretical model of the USHLP is encumbered by the fact that it is essentially a non-equilibrium process. In this regard, standard equations of state are constrained because their formulation generally presupposes equilibrium. It is therefore seemingly more appropriate to use a non-equilibrium equation of state in the model. Non equilibrium equations of state are however rendered inappropriate due to their inherent complexity and nascent development. We have therefore chosen an *ab initio* approach based on the ideal gas equation of state as a means to develop an idealised theoretical model. The developed model is thus heuristic and in the same spirit as the Carnot cycle in that, although it cannot be realised in practise, it provides a useful framework for analysis.

Approximately steady state theoretical model

The proposed theoretical model basically consists of a rigid control volume with an ideal gas flowing into and out under approximately steady state conditions. The model (Figure 1) takes into account the fact that precisely steady state conditions are difficult to achieve in practise. This aspect of reality has been expounded on by Leff, who made the case that reality is somewhat too nuanced to allow for strictly equilibrium processes (Leff and Mungan, 2018). State parameters under what are generally considered to be steady state conditions are usually subject to minor fluctuations with respect to time. This implies that these parameters are better expressed

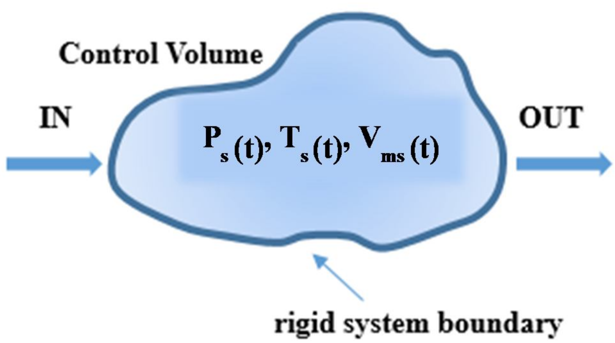

Figure 1. Approximately Steady state flow of an ideal gas through a rigid control volume.

as functions of time i.e.

Pressure = $P_s(t)$, Temperature = $T_s(t)$ and Molar Volume = $V_{ms}(t)$.

USHLP theoretical model

Introducing the unsteady state heat loading protocol to the control volume in Figure 1 will entail introducing one valve at the control volume inlet and another at the control volume outlet (Figure 2). Alternating conditions of compression and decompression can be achieved by systematically opening and closing the valves at the control volume inlet and outlet.

A key underlying assumption of the analysis presented below is that the source of the ideal gas that flows into the control volume is at a consistently higher pressure than the control volume. Furthermore and as mentioned above, it is assumed that pressure, volume and temperature are correlated by the ideal gas equation of state.

A schematic of the set up required to implement USHLP is depicted in Figure 2.

The time dependant variables pressure, temperature and volume under USHLP are here denoted as $P(t), T(t)$ and $V_m(t)$. For the purposes of analysis we consider a control volume which is initially operating under approximately steady state conditions. This control volume is taken to be initially at pressure given as:

$$P_s(t_0) = P_0, \quad (1)$$

And volume $$V_{ms0}(t_0) = V_{m0} \quad (2)$$

With temperature $$T_s(t_0) = T_0 \quad (3)$$

for a point in time denoted as t_0. The point in time t_0 is taken to coincide with the onset of USHLP. The first action associated with USHLP implementation, in this particular case, is the closing of the outlet valve (whilst

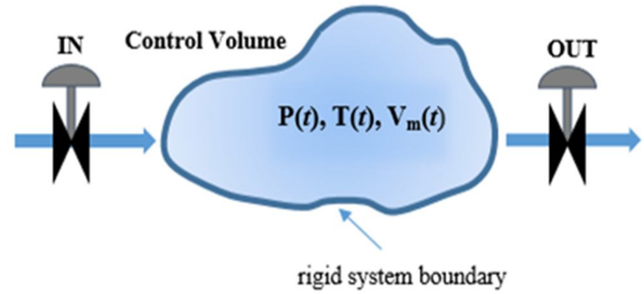

Figure 2. The USHLP set-up.

the inlet valve remains open) thereby increasing the control volume pressure from P_0 to a new pressure here denoted as P_1. This compression phase will continue up to a point in time t_1, such that

$$P(t_1) = P_1 \quad (4)$$

The increase in pressure will correspond to a reduction in the molar volume (within the control volume) from V_{m0} to V_{m1}.

The resultant change in the control volume temperature will depend on the relative change of the pressure with respect to molar volume i.e.

If $$P_1 = \alpha P_0 \quad \text{where } \alpha > 1 \quad (5)$$

And $$V_{m1} = \beta V_{m0} \quad \text{where } \beta < 1 \quad (6)$$

Then the USHLP will result in an increase in temperature in cases where $\alpha > \beta^{-1}$ such that the temperature will change from T_{s0} to a higher temperature T_1 where:

$$T_1 = \gamma T_0 \quad \text{where } \gamma > 1 \quad (7)$$

The compression phase is subsequently followed by a decompression phase in accordance to the procedure described above. This is achieved by opening the outlet valve whilst closing the inlet valve. The pressure will decrease from P_1 to a new pressure here denoted as P_2. This decompression phase will end at a point in time t_2 such that,

$$P(t_2) = P_2 \quad (8)$$

The decrease in pressure will correspond to an increase in the molar volume within the control volume from V_{m1} to V_{m2}. The resultant change in the control volume temperature will depend on the relative change of the pressure with respect to molar volume i.e.

If $$P_2 = \varepsilon P_1 \quad \text{where } \varepsilon < 1 \quad (9)$$

And $$V_{m2} = \mu V_{m1} \quad \text{where } \mu > 1 \quad (10)$$

The USHLP will result in a decrease in temperature in cases where $\varepsilon^{-1} > \mu$ such that the temperature will change from T_1 to a lower temperature T_2 where:

$$T_1 = \rho T_2 \qquad \text{where } \rho > 1 \tag{11}$$

The decompression phase from P_1 to P_2 is followed by a compression phase from that raises the pressure from P_2 to P_3. This compression ends at time t_3 such that,

$$P(t_3) = P_3 \tag{12}$$

The compression phase from P_2 to P_3 will (if it is in accordance to the criteria already defined) result in an increase in temperature from T_2 to T_3. This is in turn followed by a decompression phase which ultimately reduces the temperature from T_3 to T_4. The alternating conditions of compression and decompression persist for the duration of USHLP implementation up until the final compression *or* decompression phase with a temperature change from T_{n-1} to T_n.

The variation of temperature $T(t)$ under USHLP is of particular interest because of the relationship between the quantum of heat transferred and the temperature gradient that drives heat transfer. The time varying character of temperature in the case of USHLP implementation necessitates the calculation of the average temperature, here denoted as $\bar{T}$, for the duration of USHLP implementation. The average temperature under approximately steady state conditions is here denoted as $\bar{T}_s$. Given the above, it is conceivable that USHLP implementation can result in an average temperature that is higher than would have been otherwise achieved through steady state heat transfer ($\bar{T} > \bar{T}_s$). Figure 3 shows conjectured temperature profiles $T(t)$, $\bar{T}$ and $T_s(t)$ where,

$$\bar{T} > \bar{T}_s \tag{13}$$

The temperature profile associated with the function $T_s(t)$ depicts the minimal temperature fluctuations that are sometimes observable under conditions that are designed to be steady state.

The average approximately steady-state temperature $\bar{T}_s$ is related to the approximately steady-state temperature profile for time *t* by Equation 7:

$$\bar{T}_s = \frac{\int_0^t T_s(t)dt}{t} \tag{14}$$

It follows that the average unsteady-state temperature $\bar{T}$ is related to the unsteady-state temperature profile for time *t* by Equation 8:

$$\bar{T} = \frac{\int_0^t T(t)dt}{t} \tag{15}$$

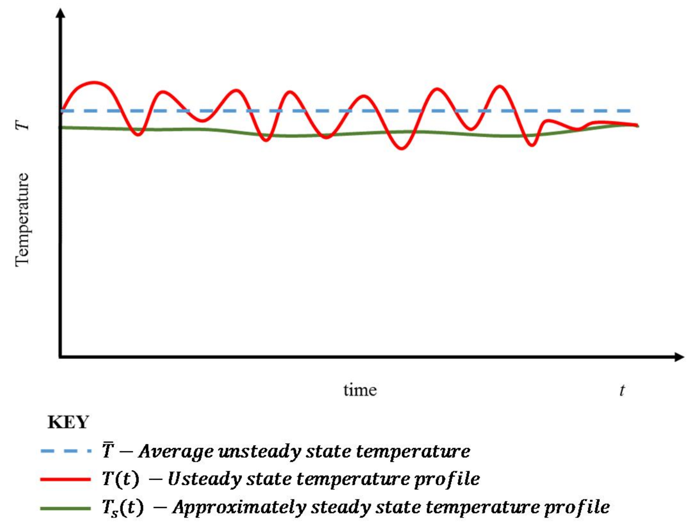

Figure 3. Comparative illustration of conjectured temperature profiles.

For simplicity we take the surrounding medium to be a heat reservoir which can absorb arbitrary amounts of energy without changing its temperature. The temperature of the surrounding medium is here denoted as T' and is assumed to be the same value for both modes of heat transfer. The rate of heat transfer under approximately steady state conditions $Q_s(t)$ is thus expressed as,

$$Q_s(t) = UA[T_s(t) - T'] \tag{16}$$

Where:

$Q_s(t)$	-	Steady-state rate of heat transfer
U	-	Overall heat transfer coefficient
A	-	Heat transfer surface area
$T_s(t)$	-	Steady-state temperature
T'	-	Temperature of surroundings

For the case of USHLP, the rate of heat transfer is given as

$$Q(t) = UA(T(t) - T') \tag{17}$$

Where:

$Q(t)$	-	Time varying USHLP rate of heat transfer
U	-	Overall heat transfer coefficient
A	-	Total heat transfer surface area
$T(t)$	-	Time varying USHLP temperature
T'	-	Temperature of surroundings

The average rate of heat transfer over approximately steady state conditions over a period t is given by Equation 10:

$$\bar{Q}_s = UA(\bar{T}_s - T') \quad (18)$$

The average rate of heat transfer over approximately steady state conditions over a period t is given by Equation 11:

$$\bar{Q}(t) = UA(\bar{T} - T') \quad (19)$$

It therefore follows that in the hypothetical case where USHLP is more efficient than steady state heat transfer

$$\bar{Q} > \bar{Q}_s \quad (20)$$

MATERIALS AND METHODS

In order to verify the theoretical model described above, experiments involving heat transfer from steam were conducted. In these experiments, heat was transferred from steam to a water evaporation process. The aim of the experiments was to compare and contrast the amount of water evaporated versus the amount steam consumed under steady state and unsteady state conditions.

Experimental setup

The apparatus consisted mainly of an electric boiler and evaporator pan with a jacket type heat exchanger (Figures 4 and 5). In the setup shown in Figure 4, steam from a boiler is injected into a jacket. As steam passes through the jacket, heat is transferred from the steam to the water in the evaporator pan. This results in an above ambient rate of evaporation of the water contained in the pan. After passing through the jacket steam leaves the jacket as a condensate. The introduction of the two valves in Figure 5 is for the purpose of implementing USHLP.

For both experimental setups a pressure gauge was installed along the steam line between the boiler and the jacket heat exchanger. In the case of the experiments with USHLP the jacket inlet valve was placed before the pressure gauge along the steam line towards the jacket. An evaporator was fabricated with an insulated jacket type heat exchanger design, facilitating heat transfer from the steam to the evaporator pan. The experimental setup was such that steam from the jacket outlet was discharged to the atmosphere.

A novel aspect of the experimental work was in achieving automated periodic opening and closing of the valves at the jacket inlet and outlet. The challenge was that the automated periodic valves had to be custom made. There is as yet no generic variety of valves that are designed to open and close at a high frequency for steam applications. Though solenoid valves with timers are available these are normally used in applications that require a closed cycle that is significantly longer than the open cycle. It should be noted however, that in experimental work subsequent to the work reported here solenoid valves have been modified and programed so as to open and close within the required frequency range.

Automated periodic expansion of steam was achieved for the experiments by way of automating ordinary manual valves. The automation of the valves was achieved by way of using two shafts to link a car wiper motor and arm system with two manual valves. The opening and closing motion of the valve was thus mechanically synchronized with what would have been the back and forth motion of wipers. A video of the experiments that implemented the USHLP can be viewed online (https://www.youtube.com/watch?v=hM90lJ7pNN8).

Procedure

At the onset of the experiments a measured amount of water was poured into the evaporator pan. This was followed by pouring a measured amount of water (to be converted into steam) into the boiler. The aim of the experiments was to compare the amount of water evaporated per amount of steam consumed for steady state and USHLP heat addition. After each experiment the amount of water evaporated and steam consumed was measured.

For experiments involving steady state heat addition steam was discharged from the boiler into the evaporator jacket at constant pressure. For experiments in which USHLP was implemented the first step involved opening the valve at the jacket inlet whist the valve at the jacket outlet was closed to allow the passage of steam into the jacket under compression. The resultant compression would consistently correspond to an increase in the pressure reading on the gauge placed along the steam line between the first and second valve. The compression phase would be followed by a decompression phase actuated by closing the jacket inlet valve whilst opening the jacket outlet valve to discharge the condensate out of the jacket. The decompression would consistently correspond to a decrease in the pressure gauge readings. Decompression would be followed by compression after a set lapse of time by closing the valve at the jacket outlet whilst opening the valve at the jacket inlet. The conditions in the jacket would alternate between compression and decompression for the duration of the experiments. Whereas there is probably an unlimited number of permutations in terms of cycle time for compression and decompression, the conducted experiments were based on a 1 second period for compression and 1 second period for decompression.

RESULTS

The periodic supply of steam to the jacket type heat

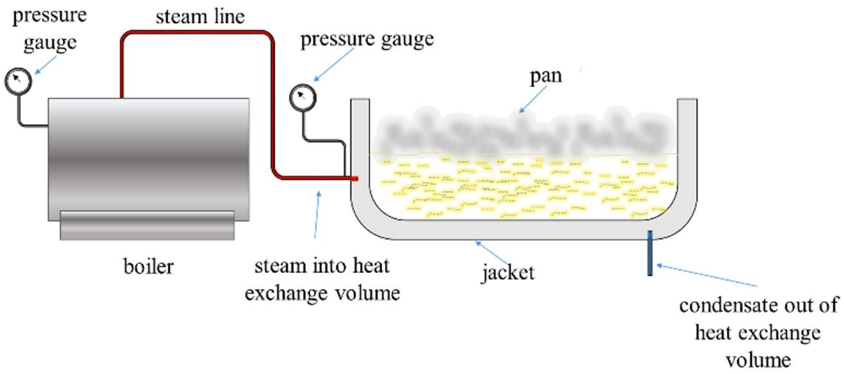

Figure 4. Schematic of evaporator with steady state heat addition.

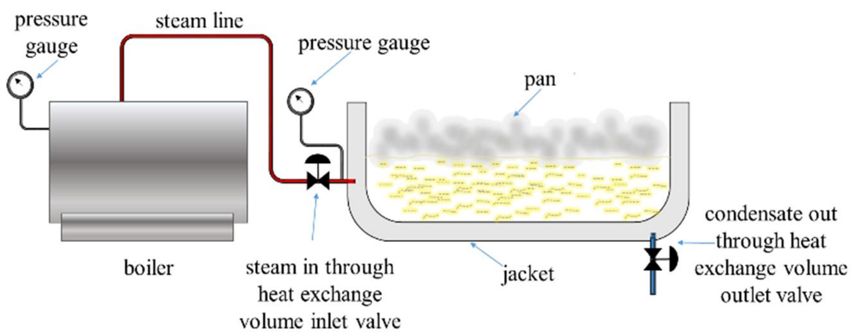

Figure 5. Schematic of evaporator with USHLP.

exchanger through opening and closing of the two valves was noted to be more efficient that continuous steam supply. It was noted that on average 0.137 kg of water were evaporated per kg of steam expended in the case of periodic supply of steam. In the case of continuous supply of steam 0.097 kg of water was evaporated per kg of steam expended. This suggests a circa 42.018% increase in efficiency from switching from continuous steam supply to periodic steam supply. The graph in Figure 6 was plotted from the experiment results.

DISCUSSION

In the context of the conducted experiments, the periodic supply of steam to the jacket type heat exchanger through opening and closing of the two valves was noted to be more efficient than continuous steam supply. The two lines in Figure 6 show that the line connecting the points associated with periodic supply of steam by the action of the two valves has a noticeably higher gradient than the points associated with continuous supply of steam. The gradient of the lines is in itself a measure of the efficiency as it is derived from the ratio of water evaporated to the amount of steam consumed.

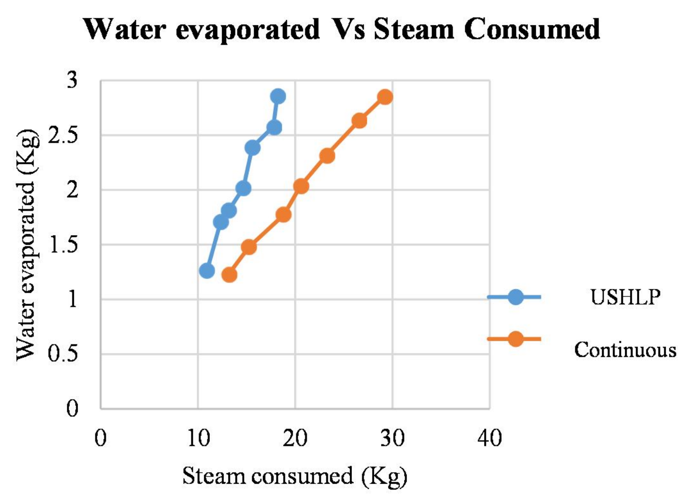

Figure 6. The graph shows the change in water evaporated with respect to steam consumed.

It follows that USHLP results in a higher heat transfer efficiency compared to continuous supply of steam and it can thus be concluded that the hypothesis expressed in Equation 20 and illustrated in Figure 3 holds. The results point to an increase in efficiency by up to 42% by transitioning from steady state heat transfer to USHLP based heat transfer.

CONCLUSION

The hypothesis that a USHLP based modus operandi for heat exchangers results in increased heat transfer efficiency as compared to one based on steady state operation was investigated. Heat exchanger efficiency was determined from a comparison of the amount of water evaporated versus steam consumed. Results from the conducted experiments point to an increase in efficiency by introducing USHLP. However, further analytical and experimental work is required in terms of evaluating the efficacy of USHLP based heat transfer. For instance, it is necessary to scale up the size of the apparatus and to test whether or not introducing USHLP at a relatively larger scale will result in efficiency gains compared to continuous supply of steam. Scaling up the apparatus and also changing the heat exchanger design from jacket type to another design will allow for a rigorous verification of USHLP. Furthermore the efficacy of USHLP relative to steam traps is as yet untested. The authors are hopeful that the work already presented will bring some attention to USHLP and will inspire independent verification of the presented results.

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