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## Evaluation of process upgrades and novel solvents for the post combustion CO<sub>2</sub> capture process in pilot-scale

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### Abstract

In this work, a number of different process upgrades have been implemented at a 1 ton/hr CO<sub>2</sub> capture test facility operating on a slipstream of flue gas from a coal-fired power plant. The benefits of the upgrades have been assessed through tests using monoethanolamine (MEA) as well as novel solvents. Amongst others the solvent cross flow heat exchanger was improved resulting in a closer temperature approach. The improvement of the heat exchanger was found only to reduce the energy requirement marginally. It was furthermore found that applying inter-stage cooling in the lower section of the absorber did not benefit the MEA process significantly, whereas with novel solvents, the regeneration energy could be reduced with up to 7%. Introducing a vapour recompression cycle on the lean solvent loop was found to lower the regeneration energy with up to 20% with MEA but to a lesser extent with novel solvents. In all cases the introduction of vapour recompression significantly increased the auxiliary power consumption. All in all, a saving in the regeneration energy of close to 25% compared to that of the standard MEA process (3.7 GJ/ton CO<sub>2</sub>) could be realised with the tested process improvements and novel solvents.

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*Keywords:* Post combustion CO<sub>2</sub> capture; pilot-scale testing; process improvements, coal flue gas, amine solvents

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### 1. Introduction

Post combustion CO<sub>2</sub> capture is today regarded as one of the more mature CO<sub>2</sub> capture technologies with large-scale demonstration projects emerging around the globe. The post combustion capture process using monoethanolamine (MEA) as a solvent is often regarded as a benchmark process, because it is a well known industrial process that has been in commercial use for decades. However, the energy requirement of the traditional MEA process remains relatively high and if applied in full-scale to power plants it will lead to substantial efficiency penalties. Therefore a lot of effort has been spent in the CO<sub>2</sub> capture community for the past 5-10 years to develop more energy efficient amine solvents and to optimize the process flow sheet. Nevertheless, not many of the

alternative solvents or proposed process upgrades have ever been tested in pilot-scale in a realistic flue gas environment.

Since 2005, DONG Energy has operated a 1 ton/hr CO<sub>2</sub> capture pilot plant facility at its Esbjerg coal-fired power plant in Denmark. The pilot plant has played a vital role in the EC supported CASTOR research project and among others demonstrated the viability of the standard MEA based CO<sub>2</sub> capture process in the tail end of a coal-fired power plant. In addition, the pilot plant has been used to evaluate the performance of novel solvents developed under the CASTOR project.

The present work is part of the ongoing EC sponsored research project CESAR [1]. The overall aim of the CESAR project is to reduce the cost of post combustion CO<sub>2</sub> capture through process optimizations and the development of more energy efficient solvents.

In this work, the possibilities of reducing the energy requirement of post combustion CO<sub>2</sub> capture through process upgrades and use of novel solvents have been investigated using a pilot plant CO<sub>2</sub> capture facility.

## 2. Test facility and test procedures

The experiments reported in this work were conducted at a 1 ton/hr CO<sub>2</sub> capture pilot plant at DONG Energy's power station in the city of Esbjerg, Denmark. The CO<sub>2</sub> capture pilot plant processes a slip stream (5000 Nm<sup>3</sup>/h) of flue gas from the Esbjerg coal-fired power station. The pilot plant is based on a traditional amine scrubbing process. The design of the pilot plant has previously been described in details [2, 3].

Since the test campaigns reported in earlier work [2, 3] were conducted, a number of different process upgrades have been implemented at the Esbjerg pilot plant. Figure 1 shows a simplified flow sheet of the Esbjerg pilot plant outlining the installed upgrades. Among others, the following three process upgrades have been installed: 1) Improvement of the solvent cross flow heat exchanger, 2) Inter-stage cooling in the absorber, 3) Lean vapour recompression cycle. These three process modifications were selected for evaluation in pilot-scale because process simulations have indicated that these upgrades displayed a positive impact on energy the requirement of the MEA process [4]. In addition, similar improvements have been suggested by some vendors [5].

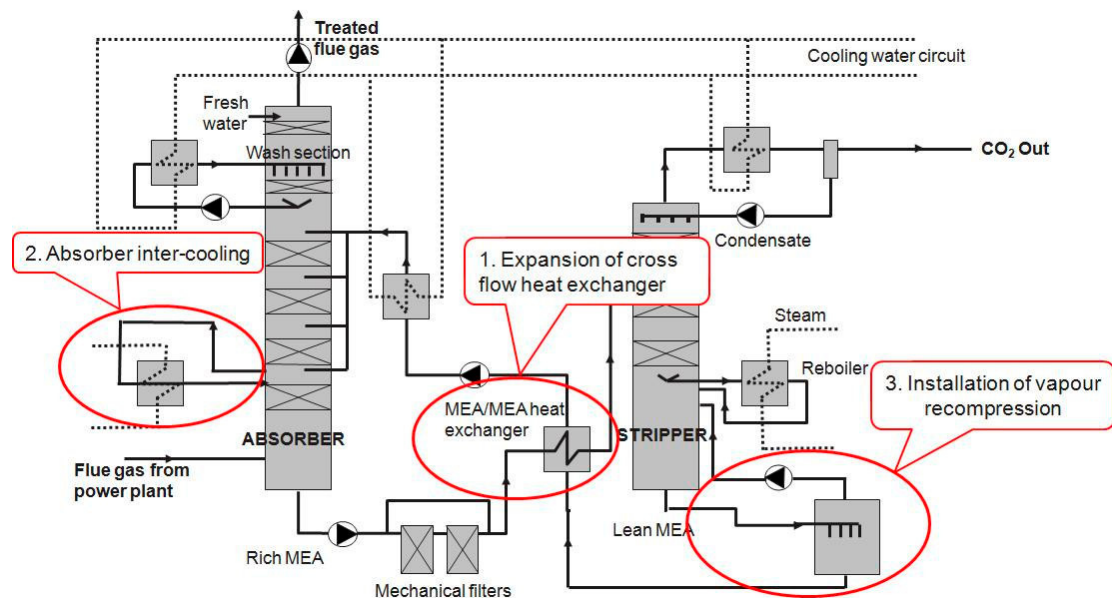


Figure 1. Schematic flow sheet of the 1 ton/hr Esbjerg CO<sub>2</sub> capture pilot plant. Three process upgrades have been installed at the pilot plant as indicated by the number 1 to 3.

The absorber at the pilot plant consists of 4 different beds. The inter-cooler is installed between the first and second bed from the bottom of the absorber as illustrated in Figure 1. The inter-cooler is able to cool the solvent to any desirable temperature down to approximately 25°C. The lean vapour recompression (LVR) cycle works in the following way: The hot regenerated solvent from the stripper bottom is flashed at reduced pressure in a flash vessel to generate vapour (mostly steam). The vapour from the flash is recompressed by the means of a mechanical compressor and injected in the stripper just below the bottom of the packing. The pressure in the flash is controlled by the compressor, which is determined by a set-point. The liquid phase from the flash (lean solvent) is returned to the cross flow heat exchanger and enters the normal lean solvent loop. The LVR cycle can be bypassed at the Esbjerg pilot plant.

Within the scope of the CESAR project, test campaigns of approximately 1000 hours duration have been conducted with three different amine solvents: 30% MEA, CESAR 1 and CESAR 2. CESAR 1 and 2 are novel amine solvents developed within the framework of the CESAR project. For each of the tested solvents, a parametric study was conducted in order to optimize the operating conditions and to investigate the impact of the different process modifications on the energy requirement for solvent regeneration. In Table 1, the parameters included in the parametric study as well as the applied variation ranges are shown.

Table 1. Overview of the parameter variation tests.

Parameter	Unit	Variation interval
Liquid-to-gas ratio (L/G)	kg/kg	1.5-4.0*
Inter-cooler temperature	°C	25-40
Flash pressure	barg	0-0.9

\*dependent on the applied solvent

Data points were only collected during steady state operation and near 90% CO<sub>2</sub> capture. Each data point is the average of 2 hours of operation in steady state. All data concerning flow, temperature, pressure and CO<sub>2</sub> concentration are continuously logged by the plant's data acquisition system. The CO<sub>2</sub> content in the flue gas varies with the load of the Esbjerg power plant. For all of the data points in this work, the CO<sub>2</sub> concentration in flue gas has been fairly constant (approximately 13% CO<sub>2</sub> dry).

### 3. Results and Discussion

#### 3.1 Improving the cross flow heat exchanger

The cross flow heat exchanger of the amine process transfers heat from the hot regenerated solvent to the rich solvent stream that is to preheat the feed stream to the stripper. Thus, improving the capacity of the heat exchanger results in more sensible energy is being recovered from the regenerated solvent. Furthermore, because of the improved cross flow heat exchanger, the inlet temperature of the lean solvent to the trim cooler will be lower, which results in a reduced cooling duty.

Figure 2 shows the temperature approach across the cross flow heat exchanger (pinch side) as a function of the absorber liquid-to-gas ratio (L/G) i.e. the solvent flow rate, during MEA testing. Data are shown from both before [3] and after the heat exchanger was improved. Data on the influence of improving heat exchanger capacity is only available for MEA as the CESAR 1 and 2 solvents were not tested in the pilot plant before the heat exchanger was modified.

It appears from Figure 2 that the temperature approach has been reduced from 7-8 to approximately 4°C depending on the solvent flow rate as a result of the improved heat exchanger. This clearly indicates that more heat is transferred across the heat exchanger. For a L/G ratio of 2.9 this corresponds to approximately 0.2 GJ/ton CO<sub>2</sub> of additional sensible heat is recovered from the regenerated solvent.

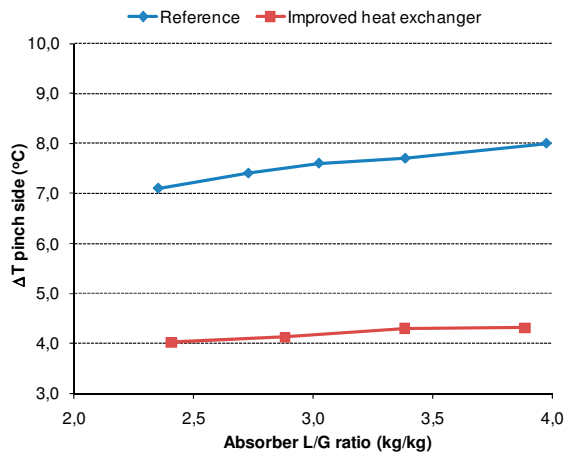


Figure 2. Temperature approach across heat exchanger (pinch side) vs. L/G during MEA operation

In Figure 3, the specific reboiler steam demand is shown as a function of L/G during MEA operation with the reference as well as the upgraded cross flow heat exchanger. Figure 3 shows that for values of L/G below approximately 2.7, the reboiler steam demand is more or less similar between the two datasets, whereas for higher L/G the data collected with the improved heat exchanger is about 0.1 GJ/ton CO<sub>2</sub> lower (saving of 2-3%). From a qualitative point-of-view this is as expected since more heat is being transferred at higher solvent circulation rates, therefore also the benefits of an improved heat exchanger should be more pronounced at higher L/G. However, as 0.2 GJ/ton CO<sub>2</sub> or more additional sensible heat is transferred to the stripper feed, Figure 2 also indicates that not all of this heat can be deducted from the reboiler duty. Presumably this is a consequence of the additional heat is not utilized very efficiently in the top of the stripper.

All in all, the saving in reboiler steam consumption seems relatively small (2-3%) by reducing the temperature approach from 7-8 to 4°C. This indicates that a cost-benefit analysis needs to be conducted to determine the optimal temperature approach.

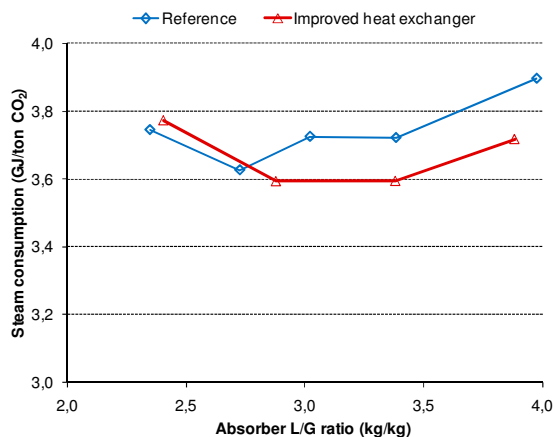


Figure 3. Reboiler steam consumption vs. L/G during MEA operation.

### 3.2 Effect of absorber inter-cooling

During CO<sub>2</sub> absorption in amine solutions a considerable temperature increase of the solvent is experienced due to the heat of absorption. This is observed as a temperature bulge near the top of absorber, which for MEA may be 20-30°C above the inlet temperature of the flue gas. The increase in solvent temperature has an adverse effect of the equilibrium CO<sub>2</sub> loading and thereby the driving force of CO<sub>2</sub> absorption. Cooling the solvent at one or multiple intermediate positions in the absorber may improve the driving force and ultimately result in increased CO<sub>2</sub> loading

of the rich solvent. Increased rich loading lead to higher cyclic CO<sub>2</sub> carrying capacity and thereby reduced regeneration energy. To investigate the impact of absorber inter-cooling, a single cooling stage was installed in the absorber approximately 4 meter above the bottom.

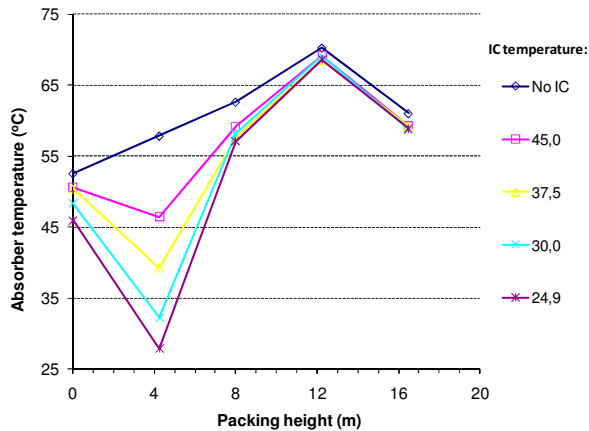


Figure 4. Absorber temperature profiles during MEA operation as a function of packing height for a number of different inter-cooler (IC) temperatures.

In Figure 4, absorber temperature profiles are shown for MEA testing at the Esbjerg pilot plant with different levels of inter-cooling (IC) ranging from no inter-cooling to inter-cooling down to 25°C. Without inter-cooling, it appears that the temperature in the bottom of the absorber is around 52°C and increasing up to a maximum of 70°C approximately 4 meters from the top. With increasing levels of inter-cooling, Figure 4 indicates that the absorber temperature is lowered significantly at the position of the inter-cooler but to a much lesser degree at the positions further away from the cooler. Nevertheless, Figure 4 indicates that the outlet temperature of the rich solvent is to some degree reduced by inter-cooling in particular in the case with inter-cooling down to 25°C, allowing in principle for higher CO<sub>2</sub> loading of the rich solvent.

In Figure 5, the reboiler steam consumption is shown as a function of the applied inter-cooler temperature for the MEA, CESAR 1 and CESAR 2 solvents. For MEA, Figure 5 indicates that the reboiler duty is more or less independent of the applied inter-cooler temperature. Only in the case of inter-cooling down to 25°C, a lower reboiler duty is obtained compared to the data point without inter-cooling. Compared to predictions by process simulators [4, 5], the observed influence of inter-cooling is much less significant with MEA. This may be a result of kinetic limitations.

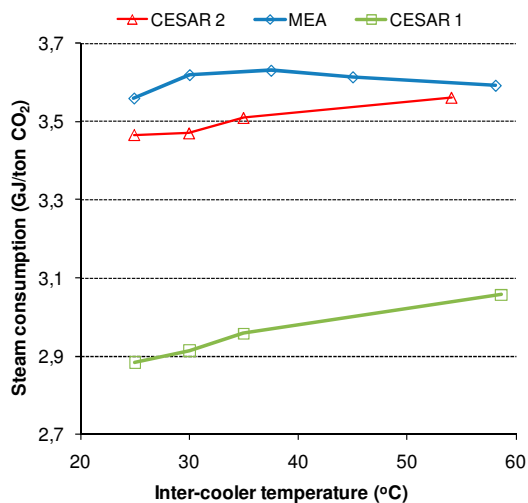


Figure 5. Specific steam demand vs. absorber inter-cooler temperature for MEA, CESAR 1 and CESAR 2.

On the contrary to the findings with MEA, a distinctive reduction of the regeneration energy is observed for the CESAR 1 and 2 solvents as the inter-cooler temperature is reduced. The effect is most pronounced with the CESAR 1 solvent, where a saving of about 0.2 GJ/ton CO<sub>2</sub> or 7% is observed for inter-cooling to 25°C. This indicates that the benefit of inter-cooling is very dependent on the specific solvent system.

### 3.3 Effect of vapour recompression

Because of the relatively high ratio of the H<sub>2</sub>O to CO<sub>2</sub> partial pressures at desorber conditions in the MEA process a substantial amount of heat is used for evaporation of water. In the lean vapour recompression (LVR) process, sensible heat from the top of the stripper is transferred to latent heat in the bottom of the stripper. Hereby the amount of heat that is used for evaporation of water is reduced. The drawback of this concept is that electrical power is required to drive the mechanical vapour compressor. Thus the benefit of lean vapour recompression depends on the saving in reboiler steam relative to the consumption of electricity by the vapour compressor.

In Figure 6 the specific steam consumption of the reboiler is depicted as a function of the applied flash pressure for MEA, CESAR 1 and CESAR 2 solvents. It is clearly seen from Figure 6 that the specific reboiler duty is dramatically reduced when the flash pressure is reduced for all solvents. However, the effect of LVR is most significant for the solvents with the higher specific reboiler duty (MEA and CESAR 2). For instances with the MEA solvent, the specific reboiler duty can be reduced from 3.6 to 2.9 GJ/ton CO<sub>2</sub> or approximately by 20%. It is not surprising that the largest steam savings are obtained for the solvents with the greater regeneration energies (MEA and CESAR 2) as these are the solvents which show the higher heat losses through water evaporation.

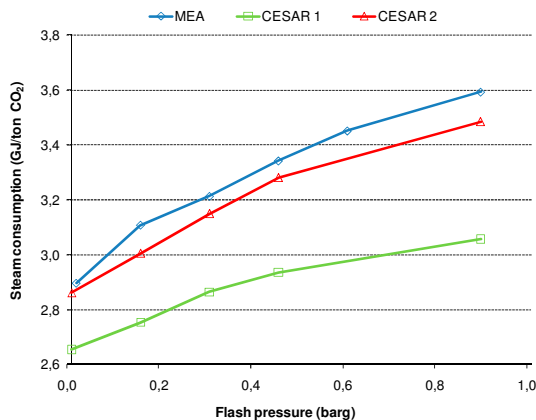


Figure 6. Specific steam demand vs. flash pressure for MEA and CESAR 1 and CESAR 2. Flash pressure of 0.9 barg corresponds to operation without LVR.

CESAR 1. How high efficiency is required before the concept is beneficial will be highly site specific. However, based on the typical value of low pressure steam, anything below 5 kW steam/kW power is not attractive. Thus, Figure 7 indicates that the LVR concept is only attractive with MEA and CESAR 2. It should be noticed that the reported power consumptions for the vapour compressor are based on the actual measured values at the Esbjerg pilot plant. For large scale applications it is possible to utilise compressors with higher mechanical efficiencies i.e. turbo compressors, which indeed will increase the overall benefits of the LVR concept.

All in all, the pilot plant tests indicate that the LVR concept is a potential option to reduce the energy demand for solvent regeneration in amine based CO<sub>2</sub> capture processes. However, as in the case with inter-cooling, the benefits of LVR will be highly dependent on the specific solvent.

In Figure 7 (left), the actual power consumption for the vapour compressor is shown as a function of the flash pressure. Figure 7 indicates that the power need for compression is increasing steeply as the flash pressure is lowered. This is as expected since, the more vapour is generated the lower the flash pressure and since the differential pressure between the stripper and flash increases. Additionally, Figure 7 (left) indicates that the power consumption is more or less independent on the applied solvent, despite the saving in reboiler duty is lower with the CESAR 1 solvent. This is further illustrated in Figure 7 (right) where the efficiency of the LVR process, i.e. steam saving per unit of power consumed, is illustrated as a function of the applied flash pressure for the different solvents. Figure 7 (right) clearly indicates that the efficiency of the LVR concept decreases with decreasing flash pressures. Furthermore it is seen that the LVR concept has the highest efficiency with MEA and lowest with

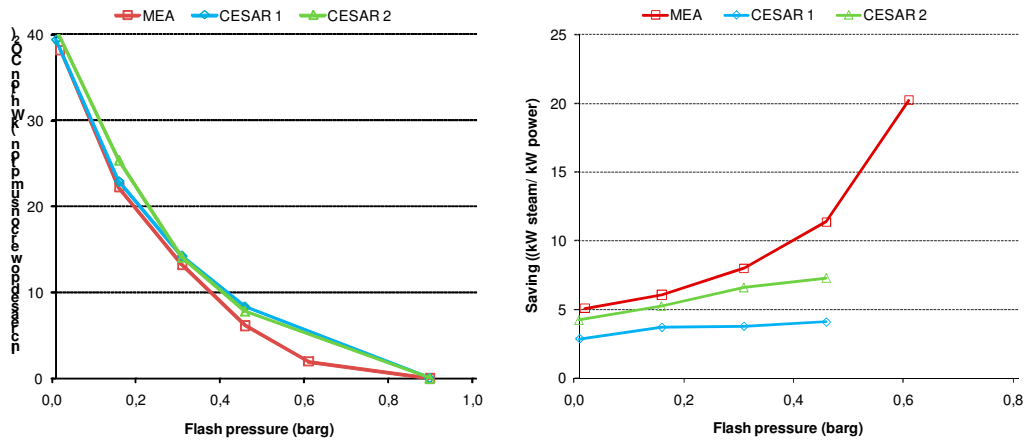


Figure 7. Left) Power consumption for vapour compressor vs. flash pressure. Right) LVR saving vs. flash pressure.

### 3.4 Influence of novel solvents

It can be seen from Figures 5 and 6 that the novel solvents offer substantial improvements in the regeneration energy relative to MEA. However the novel solvents do not behave alike. CESAR 1 is clearly the more energy efficient solvent. Without inter-cooling or LVR, a regeneration energy of 3.1 GJ/ton CO<sub>2</sub> was obtained with CESAR 1, which is an improvement relative to MEA of approximately 0.5 GJ/ton CO<sub>2</sub> or 15%. In addition, inter-cooling was observed to have a significant effect on the performance on CESAR 1, resulting in further improvement relative to MEA. When the regeneration energy of the CESAR 1 solvent with inter-cooling is compared to the reference MEA case, close to 25% improvement is obtained, i.e. 2.9 vs. 3.7 GJ/ton CO<sub>2</sub>. Furthermore the CO<sub>2</sub> carrying capacity of CESAR 1 is greater compared to that of MEA. This implies that a smaller solvent flow or lower L/G is required with CESAR 1 and thereby the cost of pumping power is reduced. It is evident from Figures 5 and 6 that CESAR 2 performed very much like MEA.

## 4. Conclusion

In this work, a number of different process upgrades have been implemented at a 1 ton/hr amine based CO<sub>2</sub> capture test facility operating on a slipstream of flue gases from a coal-fired power plant. The benefits of the upgrades have been assessed through tests using monoethanolamine (MEA) as well as novel solvents. Among others the experimental findings have indicated that reducing the temperature approach across the rich/lean amine heat exchanger from 7-8 to 4°C resulted in savings in reboiler steam demand of 1-2% with MEA. It was furthermore found that applying inter-stage cooling in the lower section of the absorber did not benefit the MEA process significantly, whereas with novel solvents, the regeneration energy could be reduced with up to 7%. Introducing a vapour recompression cycle on the lean solvent loop was found to lower the regeneration energy with up to 20% with MEA but to a lesser extent with novel solvents. In all cases the introduction of vapour recompression significantly increased the auxiliary power consumption. Even without any advanced process features, novel solvents were found to offer a significant improvement (≈15%) in the regeneration energy compared to MEA.

All in all, saving in the regeneration energy of close to 0.8 GJ/ton CO<sub>2</sub> or 25% compared to that of the standard MEA process (3.7 GJ/ton CO<sub>2</sub>) could be realised with the tested process improvements and novel solvents.

## 5. Acknowledgements

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