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Experimental Analysis of a Draft Beer Ice Bank Machine

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ABSTRACT

In a long-term established application as draft beer cooling and servicing machines, seems difficult to see any research application at first sight. However, this perspective change when one considers that the costs associated to maintenance/operating problems are very high for breweries with a very extensive network of machines. Moreover, the strong competitive market among different companies means that any cooling failure could be an opportunity for the competence. An additional aspect to consider, is that the climate and installation variability among different machines asks for a complete a-priori understanding of the unit behavior under integrated operating conditions, in order to select for each location and ambient the optimum machine (lowest cost for the brewery while keeping the cooling needs for the customer). All these statements justify a complete research analysis, based on experimental testing of the machines under different situations, in terms of beer storage temperature, room temperature, consumption profile, and integration effects (ventilation, connecting ducting lengths, etc.). Under this framework, this paper presents in detail an experimental set-up developed ex-professo for this application, showing how the different aspects have been instrumented in order to provide the needed performance parameters. Special attention has been taken to monitor the ice bank status along a particular operating and consumption scenario. To close the paper, illustrative results will be given for some representative cases, showing temperature evolution for the ambient, the inlet/outlet beer, the refrigerating system, machine consumption, ice presence at different locations, etc. From the data obtained were determined the effect of some operating conditions on the machine performance and gathered for comparison purposes. From the presented information, the level of understanding achievable with the obtained data will be clearly demonstrated, and thus the corresponding economic benefits for the breweries covering a similar research work.

1. INTRODUCTION

Cooling systems are necessary in various sectors, such as pharmaceuticals, food, and air conditioning, among others. These systems are of great importance in the beverage industry, whether alcoholic or non-alcoholic. For the cooling of beverages, standard vapor compression systems are generally used. They are widely utilized in a business that prepares and serves drinks to customers, such as bars, restaurants, pubs and nightclubs, due to the need to supply cold drinks, such as soft drinks, tea, beer, among others.

Beer is the most consumed alcoholic beverage in the world, around 78% (Gómez-Corona, 2016). The beer market contributed $114.2 Billion to the U.S. Economy in 2018 (Brewers Association, 2018). In the restaurant sector of the total consumption of beer, 65 % is draft beer, while the rest is in bottles or cans. This makes the machines used for the cooling of draft beer of great importance in order to supply the beer at a suitable temperature. The breweries have a very extensive network of these machines, which operate 24 hours a day, 365 days of the year. Furthermore, the strong competitive market between different companies means that any cooling failure could be an opportunity for the competence. Another aspect to take into account is the climatic and installation variety between the different machines. This requires a complete understanding of the behavior of the unit, in order to select the optimal machine for each location and environment.

Although cooling systems for draught drinks are widely used in the abovementioned sectors, few studies have carried out an analysis of this type of machine. Afonso and Gabriel (2014) studied experimentally the performance of this type of machine. In their work, the refrigeration system design for cooling draught was analysed in order to reduce the energy consumption and the CO2 emissions.

This work presents in detail an experimental set-up developed ex-professo for this application, showing how the different aspects have been instrumented in order to provide the needed performance parameters. Special attention has been taken to monitor the ice bank status along a particular operating and consumption scenario.

Illustrative results presented in this paper show temperature evolution for the ambient, the inlet/outlet beer, the refrigerating system, machine consumption and ice presence at different locations.

From the information presented, it is clearly demonstrated the level of understanding that the breweries could obtain on their machine by carrying out similar research work, and this would bring economic benefits to them. For this reason in this research, the authors have developed an experimental setup to study the performance of this kind of systems.

2. DRAFT BEER SYSTEM

The draft beer dispensing system is necessary to be able to supply beer at a suitable temperature to customers. The parts of a draft beer system that are used in a bar or restaurant are shown in Figure 1. Each of these parts has the following function (Beverage Craft; DraftPro Systems): the CO2 or mixed tanks (CO2 / Nitrogen) gives the pressure that allows the draft beer to be dispensed in the faucet. The primary regulator allows controlling the high pressure contained in the tanks, and with it the pressure of the beer is graduated in order to avoid the dispensing a large amount of foam. The gas lines help transport the gas from the primary regulator to the keg coupler that gives the force to dispense the beer. The gas blender allows to dispense beer with the specific gas mixture. The secondary regulator allows dispensing multiple kegs from a single gas tank. Also, the secondary regulator allows for individual pressures in each keg, helping to ensure that each keg is delivered at exactly the correct pressure. The keg coupler connects directly to the keg with an airtight seal. The coupler has two nipples: one to connect the gas line, allowing gas to be pushed into the keg. And the other to connect the beer line and that allows the beer to come out. The beer line in the system presented in this work is made up of two zones. The first one that connects the coupler with the draft beer ice bank machine. And the second one that connects the machine to the beer faucet. The refrigeration line is in contact with the beer line, to keep it at a cold temperature. Both lines are covered with thermal insulation. There are different types of beer cooling equipment, but the ice bank cooler is used in this work. These machines have the function of cooling the beer from the temperature at which the beer is in the keg until the beer reaches a suitable temperature. In the following section, this machine is explained in more detail. The draft beer tower is where the beer lines are attached to a shank or faucet (usually refrigerated). The draft beer faucet is the tap from which beer is dispensed.

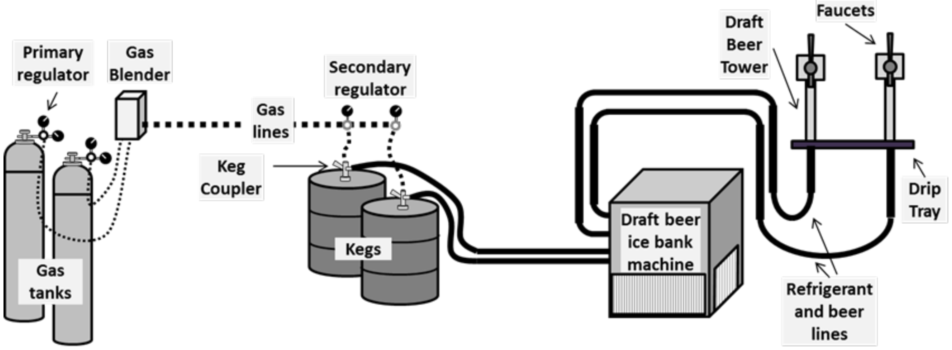

Figure 1: Schematic representation of the draft beer system

2.1 Draft beer ice bank machine

As previously mentioned, the cooling equipment used in this work is the ice bank cooler. The cooler machine is made up of two zones. The lower zone where most of the standard vapor compression refrigeration system is located, which is composed of a hermetic compressor, a capillary tube as an expansion device, and an air-refrigerant condenser. In the upper zone there is a tank that is filled with water. Immersed in this tank are the liquid-refrigerant evaporator and the coiled pipes of the beer. The number of coiled pipes varies according to the number of lines of beer (from 1 to 3 lines depending on the machine). Inside the tank there are also a stirrer and a pump. The stirrer allows the water inside the tank to be at an almost uniform temperature. The pump takes cold water from the tank and sends it through the refrigeration lines. The pump has a very important function, which is to avoid heating and possible deterioration of the beer found in the lines; the residence time of the beers in the lines will depend on the beer consumption.

In the tank, the heat exchange takes place between the evaporator and the water, and then from the water to the beer in the coiled pipe. The beer flows from the keg through the beer line to the machine, where the cooling of the beer takes place. And then the beer leaves the machine in a new beer line until it reaches the faucet that is where the beer is dispensed.

The water inside the tank is cooled by the evaporator that is at a temperature below 0 ºC. This causes the water near the evaporator to form ice. Two zones are formed inside the tank, one with ice and the other with very cold liquid water at a temperature close to 0ºC. The thickness of the ice can be adjusted by the position of the ice bank probe (ice presence detector), and thus obtain different ice masses. The ice bank probe prevents all the water inside the tank from freezing, for this, the compressor is switched off when it reaches a defined ice thickness.

These machines are in operation 24 hours a day, 365 days a year. The compressor in the refrigeration system of the machine works with on-off cycles depending on the ice present in the machine. The water flow through the beer line is permanently cooling to reduce heat gains.

3. EXPERIMENTAL SETUP

An experimental unit has been built to study draft beer ice bank machines (systems). The unit provides reliable measurements of their thermal–hydraulic performance. To carry out the experiments on the draft beer ice bank machine, parts of the previously mentioned system have been replaced. The experiments have been carried out with water as a substitute for beer, in order to avoid the waste of beer, avoid foam impact on flow measurement, and also to simplify the experimental unit. In addition to the fact that water has similar thermo-physical properties of density and heat capacity to beer (Romero, 2004; Bhuvaneswari, 2014). The fluid change means that it is no longer necessary to have a part such as CO2 tanks, primary and secondary regulator, gas lines, gas blender and the keg coupler. These parts are replaced by pumps that allow fluid movement. The beer kegs have been replaced by thermal baths.

The experimental unit is thus designed to supply hot water from the thermal bath (as beer in the keg) to a draft beer ice bank machine, and to study its cooling performance. The main objective is to study and characterize the integration effects of the unit installation in real scenarios (temperature levels, user profiles, ventilation constraints), then comparing relatively the performance under different conditions. Thus the possible minor overall performance offset due to beer substitution is eliminated by the relative comparison, while having with the suggested water loop the best control in the flow and temperature levels along experiments.

Besides the draft beer ice bank machine, the experimental unit is made up of two thermal baths, two water pumps, two flow meters, several temperature sensors, several ice sensors, valves and pipes. A schematic diagram of the experiment unit is shown in Figure 2.

The thermal baths have a working temperature range of -45 to 200 ºC, with a calorific power of 3.0 kW and a cooling capacity at 20 ° C of 0.8 kW, and a volume capacity of 22 liters. These thermal baths are linked to the draft beer ice bank machine through pipes, as shown in Figures 2 and 3a.

The system studied in this work is made up of two beer lines. The mass flow rate of water in line 1 is measured by a Coriolis mass flow meter. While line 2 uses an electromagnetic flow meter. Both flow meters with an accuracy of the actual flow within the operating range of 0.1% and 0.2%, respectively. Four calibrated K-type thermocouples with an accuracy of ±0.3 ºC are placed in each beer line in order to measure the water temperature at different positions. The thermocouples are located: (1) after the exit of the keg and just before entering the refrigerated line

(Tk); (2) before the inlet to the beer coiled pipe inside the machine (Tic); (3) after the outlet the beer coiled pipe inside the machine (Toc) and (4) at the outlet of the beer faucet (Tf). Other calibrated K-type thermocouples with an accuracy of ±0.3 ºC have been placed at different points on the machine, in order to detect the behavior of the machine under different situations of use. These sensors have been placed at the following points: one sensor at the top of the compressor shell, one sensor at the outlet of the compressor, two sensors at the middle and end of the condenser on the refrigerant side, two sensors at the front air intake of the machine. All these sensors are covered by a thermal conductive epoxy layer and thermal insulation. Some of these sensors are shown in Figure 4.

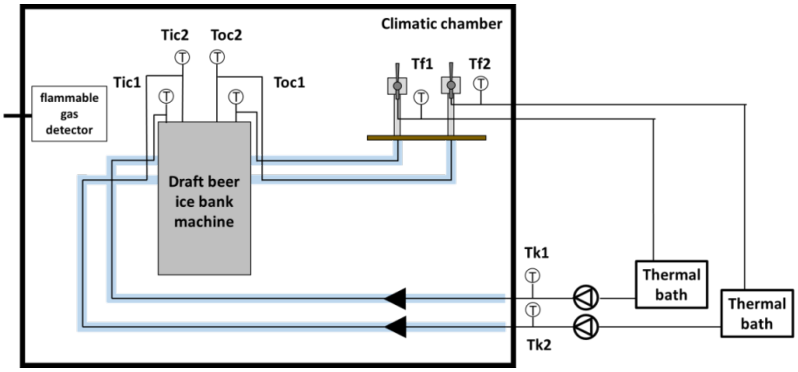

Figure 2: Schematic representation of the experimental unit

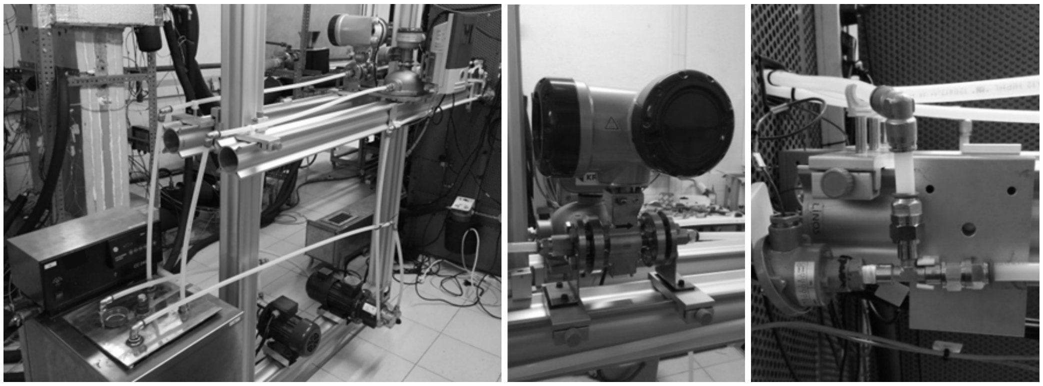

Figure 3: (a) some parts of the experimental unit; (b) electromagnetic flow meter; (c) thermocouple after the outlet of the keg

Figure 4: thermocouples at different points on the machine

In addition to the ice bank probe that controls the compressor on and off, five extra ice bank probes have been placed inside the water tank on the machine. Four of these probes are located on each side of the machine with the same opening angle as the probe used to control the compressor. The other probe is on the back side with a completely closed angle, this means that it is as close as possible to the evaporator pipe.

A power meter is used to measure the total electrical consumption of the machine. This electrical consumption includes the following equipment: the compressor, the pump for the refrigeration of the beer lines, the stirrer, the fan and the electronic components of the machine.

A pump control system has been prepared, consisting of variable frequency drives and a separate data acquisition and control system to achieve better sampling. And with this, different beer supply scenarios (constant and periodic) have been achieved. The data acquisition and control module was used coupled with a LabView data logging and control software application.

The experiments were performed in a climatic chamber in order to control the environmental conditions: the temperature of the chamber was fixed and kept constant during the experiment according to the studied ambient temperature condition. This climatic chamber is conditioned to carry out tests with machines that work with flammable gases, it has flammable gas sensors, and an evacuation and cut-off systems for the electrical current. The refrigerant propane (R-290) is used as the working fluid in the ice bank cooler.

In addition, all the elements of the experimental facility such as pipes have been fully insulated to reduce heat losses. A commercial insulation has been used (25 mm insulation thickness) for this purpose.

3.1 Experimental procedure

Before starting the experiment, the following steps must be followed: the ice bank has already been generated by the machine overnight; the climate chamber is conditioned to achieve the ambient temperature of the test; the temperatures of the thermal baths are also set in order to have hot water (substitute for beer in the keg) at the desired temperature. The experiment can be started when the parameters of the machine are stable for the temperature of the climatic chamber (machine working environment) and the temperature of the thermal bath water (keg) defined for the test.

The experiment consists of the cooling process of the hot water carried out by the draft beer ice bank machine. For this, the hot water (water that is in the thermal bath) is pumped through the beer line and passes through the coiled pipe of the beer, until finally leaving the faucet. The water mass flow depends on the beer consumption scenario studied in the test, including scenarios with constant or periodic (at different rates) beer delivery.

As previously commented, the machine has two beer coiled pipes, both of which are connected to the system, instrumented and prepared to be used in the tests. This allows to cover scenarios with the machine delivering two different beers to the customers, at different rates.

The experimental procedure used does not follow any standard method. The procedure used, focused as commented before to investigate integration and operational effects rather than characterizing the unit performance, ensures that the working conditions of this equipment are the most realistic, and satisfies the requirements of our industrial partners.

4. RESULTS

The performance of the machine is characterized by different parameters, such as the generation of the ice bank, the storage capacity and the rate of heat transfer during the supply of the beer. The authors consider that for the experimental tests carried out, the heat exchange process during the beer supply is the most relevant step to be analyzed. The non-dimensional temperature shown in the results is calculated as:

$$T^* = \frac{(T - T_{min})}{(T_{max} - T_{min})} \tag{1}$$

where Tmin is a value very close to the minimum temperature of the water inside the machine tank in all the experiments. Tmax is the temperature defined for the water that is inside the thermal bath (beer in the keg) for the selected reference test. Both are constant and unique values for all the tests and have been defined by the authors as reference operating temperatures. The τ^* value is also a non-dimensional time evolution, considering the time of the reference test, the volumetric flow value is taking as reference the average value given for adequate beer delivery and the value of electrical consumption of the machine taken as a reference is the average consumption that the machine has under normal operating conditions, given by the manufacturer. All the values of this work are presented dimensionless to preserve confidential information of our industrial partners. The values taken as a reference to generate the dimensionless are values of usual working conditions of temperatures, volumetric flow and consumption for this type of equipment.

$$\tau^* = \frac{time}{time_{ref}} \tag{2}$$

$$\dot{V}^* = \frac{\dot{V}}{\dot{V}_{ref}} \tag{3}$$

$$\dot{W}^* = \frac{\dot{W}}{\dot{W}_{ref}} \tag{4}$$

4.1 Test Conditions

The experiments for the beer cooling process are performed for a pulsating volumetric flow at the baseline rate level in both lines , for three different values of water temperature in the thermal bath (beer in the keg) of T* = 1.21, 1 and 0.71 and for three different beer consumption scenarios defined as high (HC), intermediate (IC) and low (LC) consumptions, respectively. Tests have also been carried out for two temperatures of the working environment of the machine (T*= 0.5 and 0.8). The authors have decided to cover some ventilation grills of the draft beer ice bank machine in the experiments carried out, in order to study the machine in the most unfavorable conditions of the work environment in bars and/or restaurants. In these places the lack of space causes these machines to be placed between other machines and / or next to walls that obstruct their ventilation.

4.2 Illustrative Results

For the process of heat exchange during the supply of beer different parameters of the system have been studied. A reference test has been selected. This test has an intermediate consumption scenario (IC), with a temperature of the water in the thermal bath of T*= 1 and an ambient temperature around T*= 0.8. For this test, all the information that can be obtained from the experiment is shown in Figures 5 - 7.

Figure 5a shows the evolution of the non-dimensional temperatures of the water at the two most important points for the two lines of beer, one when leaving the thermal bath (Tk) and the outlet of the faucet (Tf). The capacity of the machine to reduce the temperature of the water is also appreciated. The dashed line marks the maximum temperature at which the beer could be served to consider it adequate. In Figure 5b is shown the volumetric flow during a part of the test. The saw effect seen in figure 5a is due to the fact that when the water supply it is stopped, the sensors have heat exchange with the environment despite being thermally insulated. In the case of the Tk cools and the Tf heats up.

Figure 6 shows the evolution of the temperature at different points of the system grouped by temperature range (low and high). Figure 6a shows the temperature of the working environment in which the machine was during the test. Also, the evolution of the temperature of the water inside the tank (Ttank) and of the refrigerant at the outlet of the evaporator (Trefo) is also appreciated. Figure 6b shows the temperatures of the compressor shell (Tcsh) and the refrigerant at two positions of the condenser located at the middle (Thxm) and outlet (Thxo). And in these figures the saw effect at some of these temperatures is due to the fact that the machine continues to work and tries to recover when the supply is stopped.

In figure 7a is shown the evolution of the non-dimensional electrical consumption of the machine. In which it is appreciated how consumption increases throughout the test. Figure 7b shows the evolution of the ice presence in the ice bank probes. The figure shows how the presence of ice disappears in sensors 1 to 5 during the test and around τ^*=0.3 and no sensor marks the presence of ice. It can also be seen that the ice is melting in a non-uniform way, which can be due to many factors (ice formation, the return of the water that cools the beer lines, among other factors).

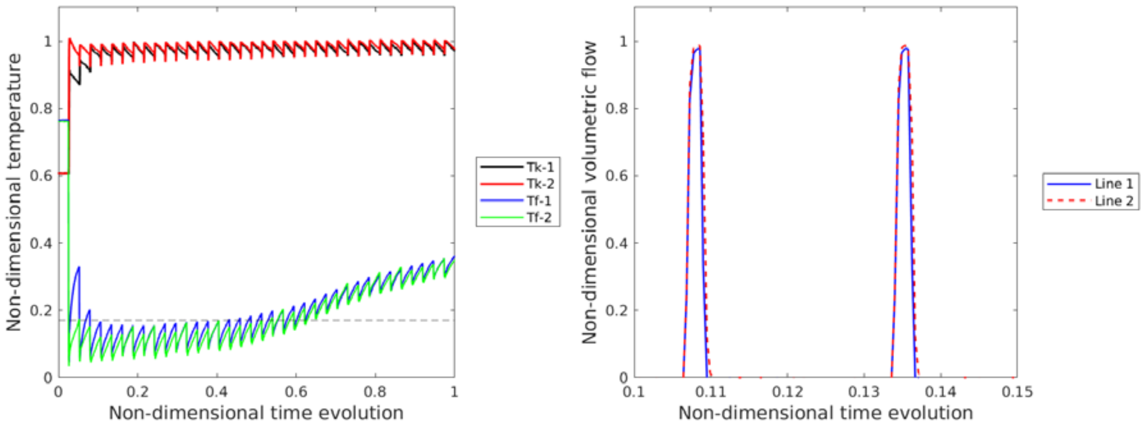

Figure 5: Reference test, transient evolution of: (a) the inlet and outlet non-dimensional temperature of the water in the beer circuit; (b) the non-dimensional volumetric flow rate during a part of the test

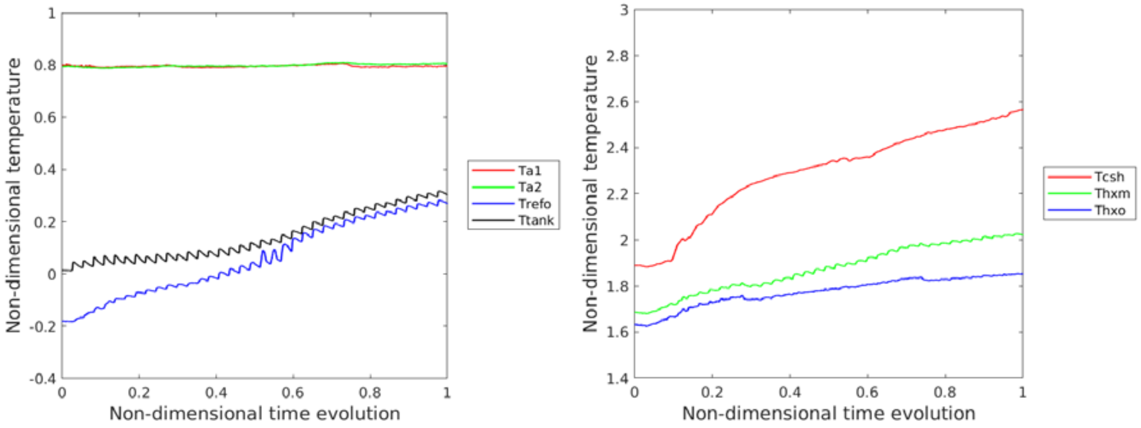

Figure 6: Reference test, transient evolution of the non-dimensional temperature at different positions grouped by temperature range: (a) low temperatures; (b) high temperatures

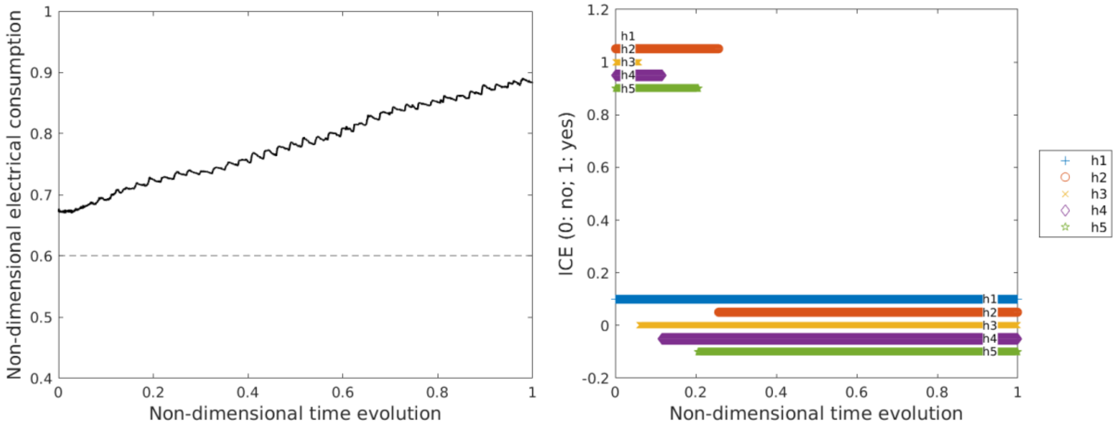

Figure 7: Reference test, transient evolution of: (a) non-dimensional power consumption of the machine; (b) the ice presence in the ice bank probe

Figures 8 and 9 show the information obtained in the experimental tests with different temperatures of the water in the thermal bath, maintaining the same scenarios of beer consumption (IC) and ambient temperature as in the reference test. Figures 8a and 9a show the evolution of non-dimensional Tk and Tf in the beer line for a temperature

Tk set at T*=1.21 and T*=0.71. The times in which the maximum temperature suitable for serving beer is reached vary, in the case of T*=1.21 the time is reduced and in the case of T*=0.71 it increases with respect to the reference test. Figure 8b shows the non-dimensional temperature of the sensor at the faucet outlet (Tf) when the pumps are activated for the two lines of beer. The saw effect occurs when the pumps are off as previously commented. Figure 9b shows the evolution of the ice presence in the ice bank probe for the test with Tk set at T*=0.71. In this test, the ice bank probe (h5) indicated the presence of ice throughout the test.

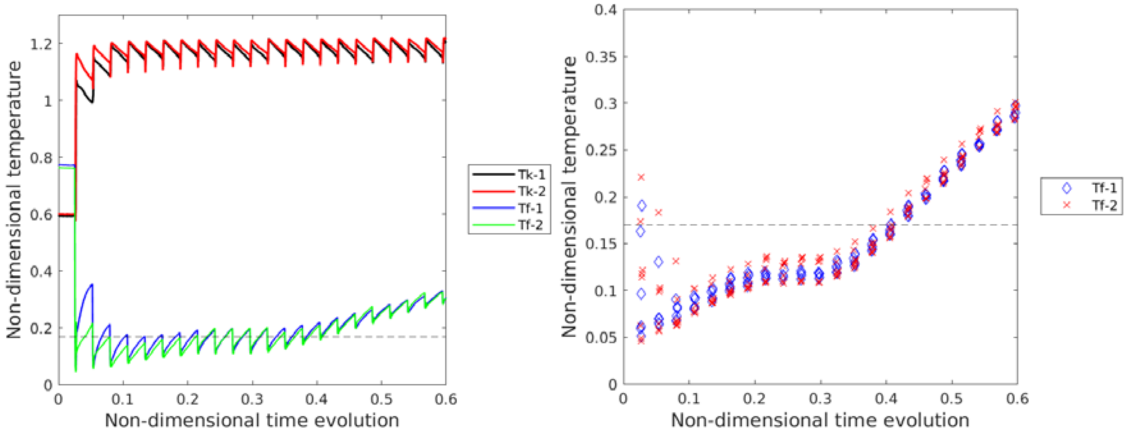

Figure 8: Test with Tk around T*=1.21, transient evolution of the non-dimensional temperature of: (a) the inlet and outlet of the water in the beer circuit; (b) the outlet when the pumps are activated

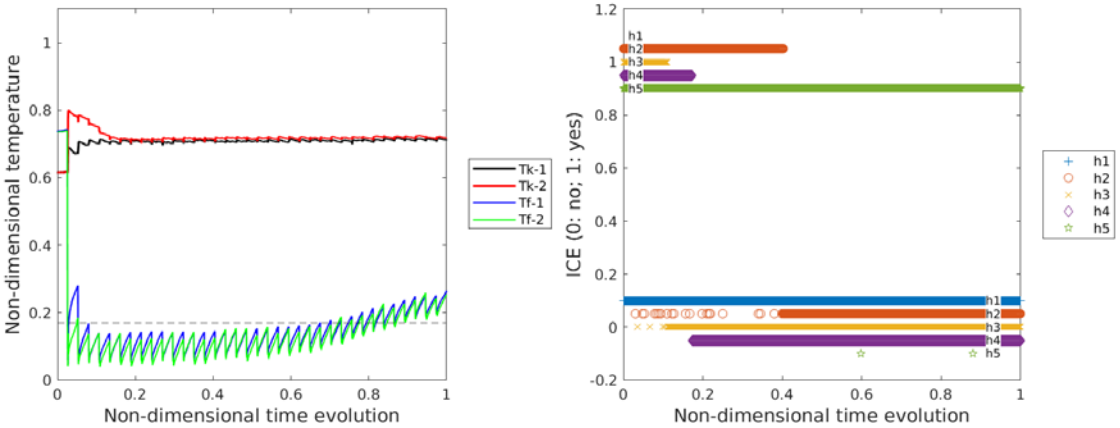

Figure 9: Test with Tk around T*=0.71, transient evolution of: (a) the inlet and outlet non-dimensional temperature of the water in the beer circuit; (b) the ice presence in the ice bank probe

Figure 10 shows the information obtained in the experimental test with an ambient temperature different from the reference case, maintaining the same scenarios of beer consumption (IC) and water temperature in the thermal baths (T*=1) as in the reference test. The ambient temperature used in this test was around T*=0.6. Figure 10a shows the evolution of non-dimensional Tk and Tf in the beer line. The time in which the maximum temperature suitable for serving beer is reached increases with respect to the reference case. A similar increase in the time that ice is present can be seen in figure 10b.

Figures 11 and 12 show information obtained in the experimental tests with different beer consumption scenarios (HC and LC), maintaining the same temperature of the water in the thermal baths and ambient temperature as in the reference test. Figure 11 shows the evolution of the non-dimensional Tk and Tf in the beer line and, as expected, the time differences between the scenarios at which the maximum temperature suitable for serving the beer is reached is appreciated. Figure 11b shows that the saw effect is greater than in the other tests, this is because the waiting time between services is longer. Figure 12 shows the difference of the volumetric flow of the different beer consumption scenarios during a part of the test. In the low consumption scenario, see Figure 12b, it can be seen that there is a difference in consumption between the beer lines.

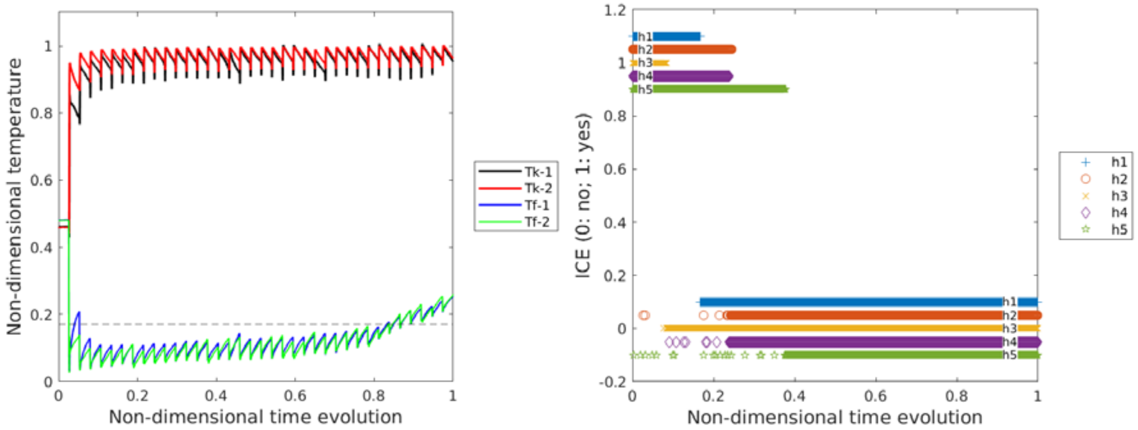

Figure 10: Test with Ta around T*=0.60, transient evolution of: (a) the inlet and outlet non-dimensional temperature of the water in the beer circuit; (b) the ice presence in the ice bank probe

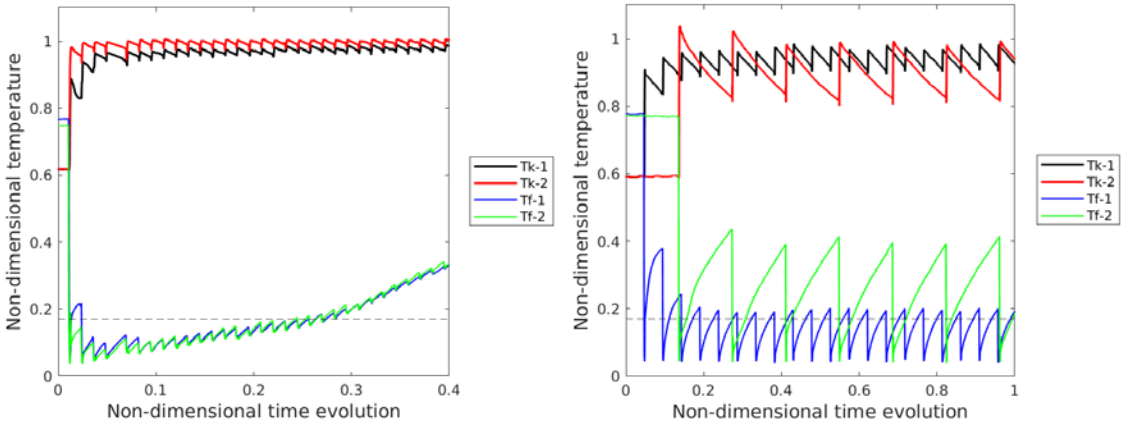

Figure 11: Transient evolution of the inlet and outlet non-dimensional temperature of the water in the beer circuit for different beer consumption scenarios: (a) high consumption; (b) low consumption

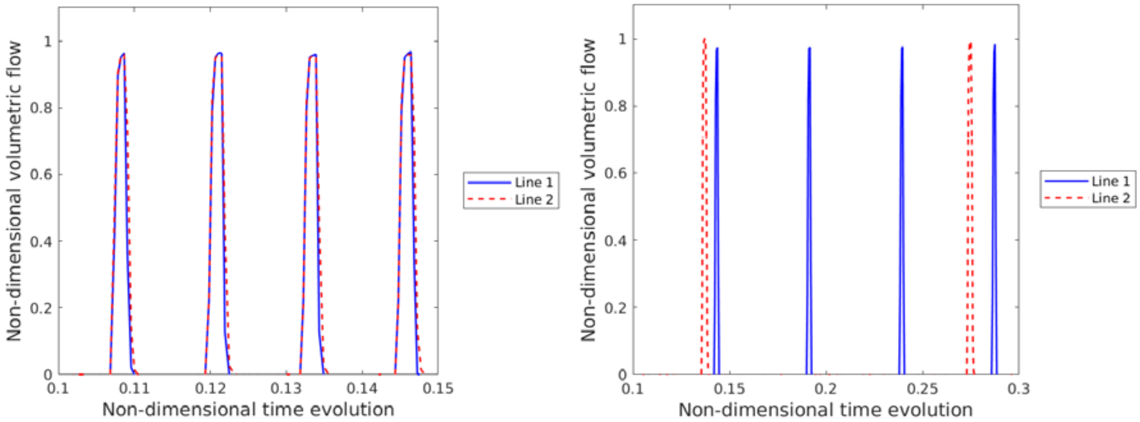

Figure 12: Transient evolution of the non-dimensional volumetric flow rate during a part of the test for different beer consumption scenarios: (a) high consumption; (b) low consumption

6. CONCLUSIONS

In this work, an experimental setup for the study of draft beer cooling systems has been developed. The experimental unit provides reliable measurements of temperatures in different locations of the system (inside the beer line and in the cold machine), the electrical consumption of the machine and the evolution of the presence of ice, to study the capacity of the machine to cool the beer. Tests of the beer cooling process were performed to determine the effect of beer consumption scenarios and beer temperatures in the keg and the environment in which the machine works on machine performance. Concluding the importance of all these parameters studied in the ability to achieve supply the beer at the right temperature for as long as possible. The experimental setup has been constructed to design and study the performance of different machines under several operational conditions. The conclusions obtained in this work, focused on relative impact of changing operational and integration conditions, would remain the same even if the working fluid had been beer instead of water, while water has similar thermo-physical properties to beer. The purpose of this work is to serve as a guide or help for beverage cooling systems integration/operation, because in many cases the design conditions of these equipment have little similarity to the real working conditions. An final map of the suitability/selection of a machine under different integration and operational conditions would be the main end output of this work.

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