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EXPERIMENTAL EVALUATION OF THE THERMAL BEHAVIOR OF HOT WATER FLOW IN A MODULE-FAUCET SYSTEM

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Abstract. *An experimental study was carried out on temperature and heat transfer in a coupled module-faucet system, under controlled conditions, during the use of purified hot water from a product marketed in Brazil. The system is composed of a module, responsible for heating, cooling, and/or gasifying the purified water, which is connected by hoses to a faucet. Temperature measurements were taken along the system, which was instrumented with thermocouples and connected to a data acquisition system. Initially, tests were performed for different purposes. In the first test, the system was evaluated under steady-state conditions to determine the uncertainties of the thermocouples. In the second and third tests, the behavior of the temperature at each thermocouple was evaluated during defined periods or until the reservoirs were emptied. Finally, to determine the operational factors that most impact the heat transfer of hot water flow, from the water outlet of the module to the final outlet at the faucet, a 2^3 factorial design was performed. For this, the factors evaluated were the two programmed temperatures of the module and the volume of hot water removed from the module. The results showed that the removed water volume has the greatest influence on the heat transfer rate, with higher heat transfer rates for small volumes compared to larger volumes. In addition, it was observed that the hose used for water flow in the module-faucet system has high thermal conductivity, which allows for greater heat transfer from the water to the surrounding environment. The study can contribute to improvements and development of new technologies in similar products to the one analyzed.*

Keywords: *Heat transfer, Module-faucet System, Factorial Design*

1. INTRODUCTION

Equipment that allows heating or cooling of water is widely used in everyday life and has been the subject of study regarding heat transfer and energy efficiency. Understanding heat transfer in coupled systems, where the hot or cold-water production equipment is connected through hoses or pipes to other water distribution devices, is still under investigation in many engineering applications. Therefore, it is not sufficient for the equipment to have good thermoenergetic efficiency if the distribution pipeline or hose has low thermal efficiency.

Some studies illustrate heat transfer in pipelines, mainly in the flow of hot water. The work by Bocian et al. (2022) identified excessive heat losses in the piping system of hot water circulation in residential buildings, which could be reduced through more efficient thermal insulation and a reduction in duct length. Moss and Cristoph (2022) evaluated measures to improve the efficiency of hot water usage in residences, such as hot water recirculation and pipe insulation, which would minimize heat losses and domestic energy consumption. Wang (2022) showed that heat loss in pipelines increases with the length of the pipe, being nearly proportional to thermal conductivity and inversely proportional to insulation thickness. It also highlighted that the relative heat loss along or through the pipe decreases with increasing pipe diameter, initial temperature, flow velocity, or surrounding temperature. Hiller (2011) experimentally assessed heat loss from pipes under various temperature and flow conditions, with different levels of insulation. They emphasized that energy loss effects go beyond the energy loss in the pipe itself and include, for example, increases in tank heat loss caused by the need to set higher temperatures to overcome the temperature drop of the flowing water through the pipe.

In this context, the present study presents an experimental investigation in a coupled module-faucet system under controlled conditions, using purified hot water from a product marketed in Brazil. The system consists of a module – which is responsible for heating, cooling, and/or carbonating purified water – connected to a faucet through hoses. The objective of the study was to analyze the thermal behavior of the flow of purified hot water through the module-faucet system, to determine factors that influence the heat transfer rate occurring from the outlet of the purified hot water from the module to the end of the faucet.

2. MATERIALS AND METHODS

2.1 Characterization of the study object

The analyzed system is the faucet-module of a product sold in Brazil. Figure 1 (a) depicts the faucet-module system with its main components separated, while Figure 1 (b) illustrates the diagram of the system connected through hoses and installed in a cabinet with a sink. Potable water from the water supply network first passes through the purification filter, transforming into purified water. It then enters the module and is directed to the heating, cooling, or carbonation reservoirs. As a result, the system can provide different versions of purified water: hot, chilled, or chilled with carbonation. Each version of water has a hose that directs the flow from the module's outlet to the faucet faucet. It is also possible to obtain potable water directly from the water supply network at the faucet, bypassing the purification filter and module.

The product offers the possibility of adjusting the temperature settings in the module, allowing variations of 1°C within the range of 86 to 99°C for purified hot water, T_h, and 3°C to 15°C for purified cold water, T_c, and/or carbonated water. Since the study focuses on purified water, from this point forward, we will refer to it simply as hot or cold water.

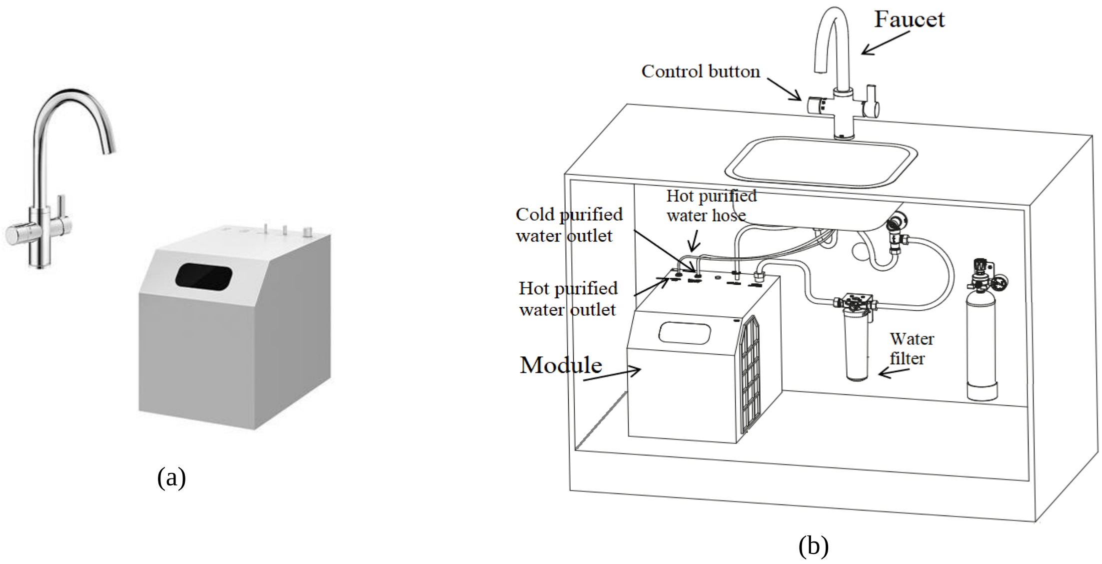

Figure 1. (a) Faucet and water heating/cooling module. *From Datasheet DocolPronto*; (b) Scheme of the coupled module-faucet system. *Adapted from Datasheet DocolPronto*.

2.2 Instrumentation

The system was instrumented with thermocouples in a laboratory under controlled conditions (Fialho, 2010). The product was installed in a kitchen sink simulating the real usability situation. Twelve type K thermocouples were used, identified as T1, T2, ..., up to T12, and arranged along the module-faucet coupled system, as shown in Figure 2. The thermocouples were fixed near the water heating reservoir (Figure 2(a)), in the hot water flow hose (Figure 2(b)), which connects the module to the faucet, and inside the faucet (Figure 2(c)). For reading and data acquisition from the thermocouples, an Extech TM500 datalogger model was used. The used model has the capability of simultaneously reading all 12 thermocouples and recording data at programmable periods and time intervals.

2.3 Experimental procedure

The module-faucet system was instrumented by attaching thermocouples to the points indicated in Figure 2, in order to identify the heat exchange of the system when the hot water mode of the product is used. After turning on the product, with the default configuration of T_h = 86 °C and T_c = 3 °C for the module, and with the thermocouples connected to the datalogger, data acquisitions were performed. The first three tests were conducted to analyze the behavior of the thermocouples and the system, while the last one aimed to perform an analysis of factors influencing the heat transfer of the hot water flow, from the module outlet to the faucet outlet.

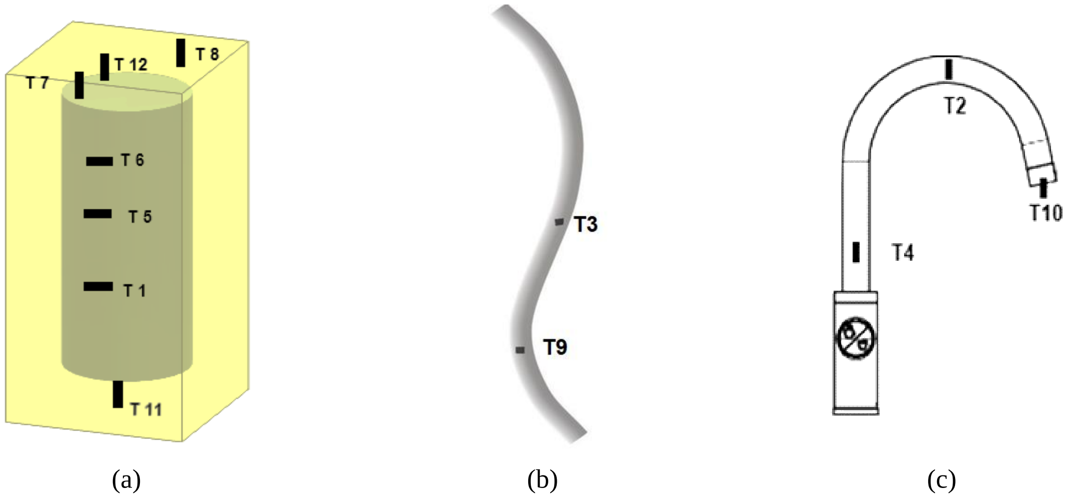

Figure 2. Arrangement of the thermocouples in the module: (a) next to the water heating reservoir; (b) in the hot water hose; (c) at the faucet.

2.3.1 First test

This acquisition was performed with the system in steady-state condition, without water flow. Temperature data were recorded every 2 seconds over a total period of 20 minutes. The purpose of the first test was to evaluate the behavior of the system temperatures in steady-state condition, determining the uncertainties of the thermocouples by calculating the standard deviation (SD) for each of them.

2.3.2 Second Test

After the completion of the first test, data acquisition from the system in use began for pre-established periods of 5 minutes. During the first 1 minute and 40 seconds, the water activation button remained on, and water flowed out. After this initial period, the button was turned off, stopping the water flow until the end of the period. Once again, data was recorded every 2 seconds. The default module configuration was maintained (T_h = 86 °C and T_c = 3 °C), and the sequence of water versions flowing out was as follows: tap water at room temperature, cold water, and hot water. For each water version released from the faucet, two replicate was performed. The purpose of this test cycle was to evaluate the temperature behavior at each thermocouple.

2.3.3 Third test

Next, the recording period lasted 5 minutes, with data acquisition every 2 seconds, with two replicates for the versions of cold and hot water. In this data collection, the objective was to evaluate the temperature behavior until all the cold or hot water was emptied from each reservoir, keeping the faucet button pressed until no water flowed out of the faucet anymore.

2.3.4 Factorial Design

The objective of this stage was to determine which factors (and their combinations) influenced the heat transfer rate in the flow of hot water. We can say that a system acts as a function, for which we seek the response in terms of the factors, which are our variables. For this purpose, the factors to be controlled were initially chosen, which can be qualitative or quantitative, as well as the responses we aim to find.

The 2^k factorial design involves "k" controlled variables (factors) that vary at two different levels. It requires conducting 2^k different trials to obtain the responses using all possible combinations of the levels. This list of combinations is called a design matrix. For the experiments in the coupled module-faucet system, three controlled variables were defined, resulting in a 2^3 factorial design. Therefore, all tests were conducted only with hot water to determine the response of the 2^3 factorial design, which in this case was the heat transfer rate during the flow in the system.

The defined factors were the volume of water flowing through the faucet, V, while the activation button was on, and the temperatures of the hot and cold water set on the module panel, T_h and T_c, respectively. In the two-level factorial design, the lower level was identified as -1 and the upper level as +1, as shown in Table 1.

The choice of values for the lower and upper temperature levels was decided according to the technical characteristics of the product provided through the manual and datasheet available on the brand's website (*Datasheet DocolPronto*). The number of trials for 2^3 full factorial design is 8 trials. The literature suggests conducting replication measurements to estimate the error of an experimental response (Montgomery, 2017). Estimating this error is important for determining the presence of effects on the factors. In the experiments conducted, two replicates were used to ensure greater confidence in the obtained results, totaling 16 experiments. The design matrix containing all combinations and the order of test execution is presented in table 2. As the response of the factorial experiment, the heat transfer rate, $\dot{Q}$ [W], was calculated during the flow of hot water using the following equation (Cengel and Ghajar, 2009):

$$\dot{Q} = \dot{m} c_p (T_e - T_s), \tag{1}$$

where $\dot{m}$ = 2.9×10^{-5} kg/s is the mass flow rate (obtained from Datasheet DocolPronto), the specific heat at constant pressure c_p = 4.21 kJ/(kg°C), T_e is the average temperature at the cross-section at the inlet of the hose, and T_s is the average temperature at the cross-section at the outlet of the hose.

Table 1. Factor/Level Relationship

Factors	**Level**	
	-1	**+1**
$\boldsymbol{V}$ (ml)	300	1000
$\boldsymbol{T_c}$ (°C)	3	10
$\boldsymbol{T_h}$ (°C)	86	99

Table 2. Coded matrix of the full factorial design.

Tests	$\boldsymbol{V}$	$\boldsymbol{T_c}$	$\boldsymbol{T_h}$
1, 2	-1	-1	-1
3, 4	+1	-1	-1
5, 6	-1	+1	-1
7, 8	+1	+1	-1
9, 10	-1	-1	+1
11, 12	+1	-1	+1
13, 14	-1	+1	+1
15, 16	+1	+1	+1

To assess the results obtained from the factorial experiment, the Origin software (OriginPro) along with the DOE (Design of Experiments) extension, was used for statistical analysis.

3. RESULTS AND DISCUSSIONS

3.1 Initial assessments

Initial tests were aimed at determining the uncertainties of the thermocouples and the behavior of temperatures throughout the system, while keeping the configuration of the module parameters fixed, with T_h = 86 °C and T_c = 3 °C.

In the first test, the system remained in steady-state, and in the other two tests, the flow of hot or cold water was released. Temperature recording was performed for each of the 12 thermocouples distributed among the module, the purified hot water hose, and the faucet within the specified time range, as stated in item 2.3. With the obtained data, it was possible to calculate the standard deviation (SD) and observe the temperature profiles over time. It is important to highlight that the only thermocouples directly in contact with water or steam were T12 (hot water outlet of the module) and T10 (hot or cold-water outlet of the faucet).

Table 3. Average temperatures and standard deviation (SD) of each thermocouple.

Temperature (°C)	**Thermocouples**											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**
Average	36.08	22.55	24.35	23.03	43.75	63.07	85.80	37.33	25.56	22.24	68.48	85.26
SD	± 0.86	± 0.49	± 0.37	± 0.72	± 0.67	± 0.65	± 0.57	± 0.05	± 0.97	± 0.11	± 0.75	± 0.57

We can observe that thermocouples T1, T4, T9, and T11 exhibit the largest deviations. This dispersion may occur due to the thermal conductivity of the material to which the thermocouple is in contact and the proximity to the heated purified water reservoir, as the reservoir operates in cycles to maintain the temperature of the water even when the system is in a steady state.

By calculating the standard deviation for each thermocouple, we were able to analyze the temperature behavior of the individual thermocouples during the subsequent experiments. Consequently, the second experimental test was carried out, involving the flow of potable water (sourced directly from the water supply network and bypassing the module) as well as hot or cold water for a duration of 100 seconds. Following this interval, the control button was deactivated until the completion of a 5 minute period. For convenience, only a few temperature profiles are shown and analyzed in this article, which are thermocouples T2, T9, T10, and T12, as shown in Figure 3.

The thermocouple T2, in contact with the hot water hose and the potable water from the water supply network (WSN) – retained inside the faucet – records a maximum temperature of 48°C, while the flow temperature is 82°C, indicating that the water from the network is a potential source of heat loss in the system, as shown in Figure 3(a).

Regarding T9, we can observe that in the initial approximately 8 seconds, the temperatures remained stable because the water had not yet reached the measuring location, as shown in Figure 3(b). After that, for the hot water, it was noticed that the temperature increased to approximately 77°C in 80 seconds, and then decreased, although there was still hot water flow until 100 seconds. The temperature drop during this 20-second interval is justified by the entry of purified water into the heating reservoir to compensate for the output of hot water, which is at room temperature. For the flow of cold water, the temperature on the surface of the hot water hose decreases by about 3°C, indicating the importance of thermal insulation for this hose to avoid affecting the temperature during a subsequent withdrawal of hot water from the system. After 100 seconds, the fluid stopped flowing, and the temperatures tended to decrease.

The temperature profiles for thermocouples T10 and T12, located at the water outlet positions of the faucet (which can be hot, cold, or at room temperature) and the hot water outlet of the module, respectively, are shown in Figure 3(c) and Figure 3(d). It can be observed that for T10 (Figure 3(c)), which directly measures the temperatures of the water coming out of the faucet, the module's set temperatures (T_h = 86 °C and T_c = 3 °C) were not reached. This is because the system loses heat (in the case of hot water) or gains heat (in the case of cold water) to/from the surrounding environment, resulting in a maximum temperature of 82°C for hot water and a minimum of 5°C for cold water. From Figure 3(d), for T12, it is observed that the flow of cold water did not influence the temperature of the hot water at the module's outlet, indicating that the thermal insulation between the reservoirs of the module seems to be sufficient. The hot water came out at a high temperature, close to 85°C, but decreased as ambient temperature water entered the heating reservoir to supply the hot water outlet through the faucet. When the faucet control button was turned off, the flow of hot water stopped, but the water in the reservoir continued to heat up, leading to the formation of steam at the top of the reservoir and at the module's outlet. Due to the convective movement of the steam, there are fluctuations in the measured temperature values, as observed in Figure 3(d).

In the third experiment, the hot and cold-water reservoirs were emptied. It was observed that when the flow of cold water was released through the faucet until the cold-water reservoir was completely empty; there was little change in the readings of the thermocouples placed in the module near the hot water reservoir, as well as in the thermocouple present in the insulation between the hot and cold-water reservoirs."

According to Figure 4(a), the readings from T9 indicated that, for hot water, it was observed that the hose starts to increase in temperature 10 seconds after the activation of the hot water button. The temperature increased to approximately 78°C around 90 seconds, and then decreased, although there was still a flow of hot water until around 125 seconds.

For T10, it can be observed that the temperature readings remained close to those set in the module (T_h = 86 °C and T_c = 3 °C) for a period, as shown in Figure 4(b). Between 100 and 150 seconds, deflections in the curves can be noticed, both for hot and cold water, coinciding once again with the end of water flow through the faucet.

According to Figure 4(c), for T12, the flow of cold water did not influence the temperature of the hot water outlet from the module. It was observed that hot water exits with a temperature close to 86ºC but decreases as purified water at room temperature enters the heating reservoir to replenish the hot water output through the faucet. Again, there are fluctuations in the temperature values after turning off the activation button on the faucet, due to convective movement of the vapor.

Comparing the temperature profiles obtained by thermocouples T10 and T12 during the faucet activation period – approximately 90 seconds – it was noticed that there was heat loss in the hose between the hot water outlet from the module, measured by T12, and the outlet through the faucet, T10. Thermocouple T10 recorded lower temperatures than T12, a difference that indicates the absence of thermal insulation in the hose allows heat transfer to the environment before the water reaches the faucet outlet.

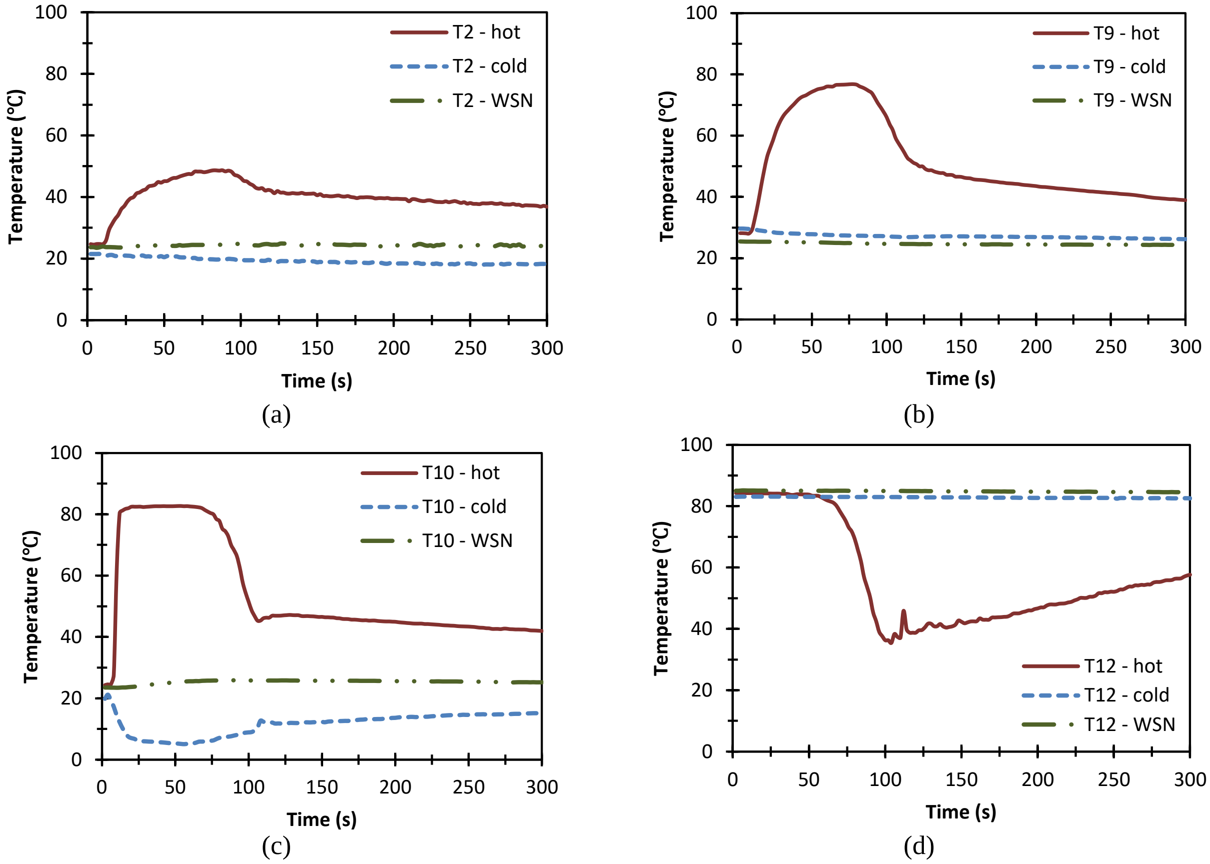

Figure 3. Temperature profiles recorded by the thermocouples in the second test: (a) T2; (b) T9; (c) T10; and (d) T12.

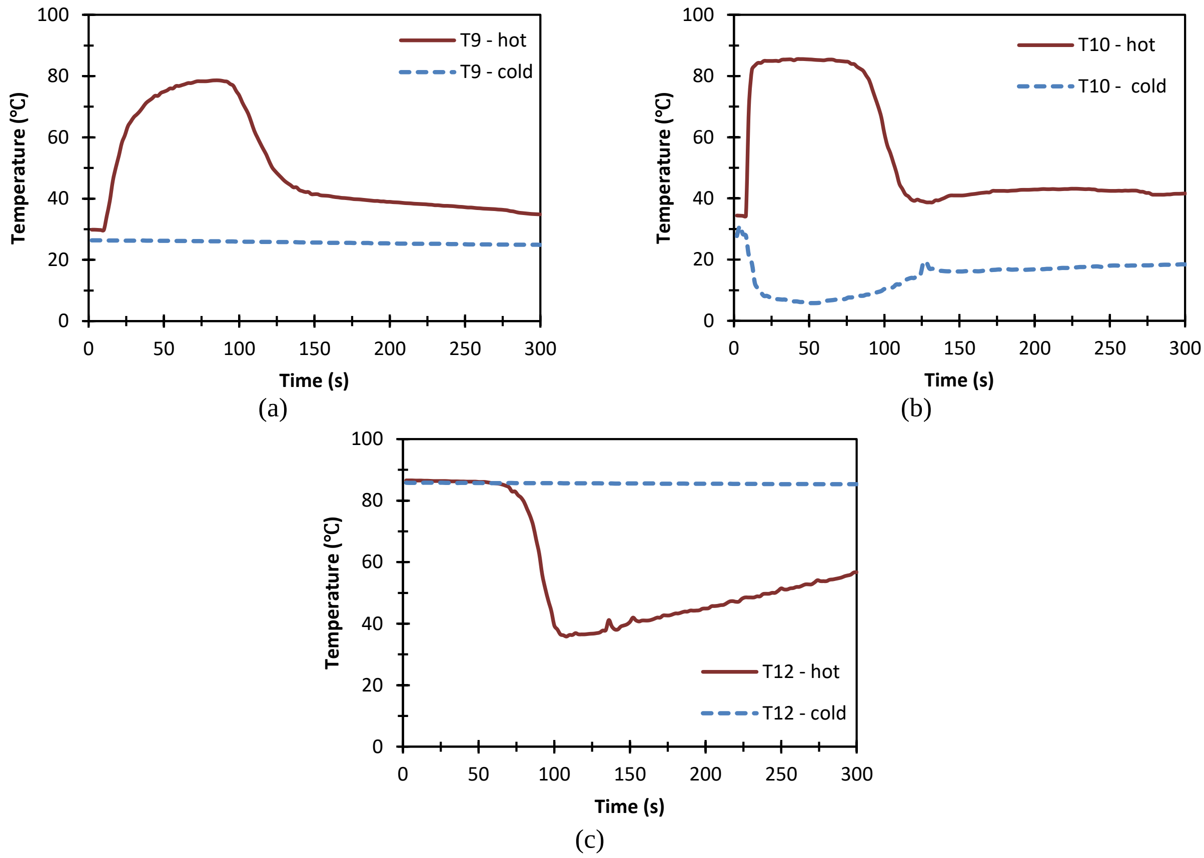

Figure 4. Temperature profiles recorded by the thermocouples in the third test: (a) T9; (b) T10; (c) T12.

3.2 Factorial Design

In this stage, the data used to calculate heat transfer are readings from thermocouples T10 and T12. During the factorial experiment, the system was allowed to stabilize before each data collection stage, ensuring that the same temperatures were always set in the module for T_c and T_h.

By performing the 2^3 factorial experiment with replication, the average temperatures of the thermocouples were obtained as shown in Table 4. The average temperatures at the inlet and outlet cross-sections, T_e and T_s, were obtained respectively from the readings of thermocouples T12 and T10. With these temperatures and using equation 1, the heat transfer rate was calculated for each test.

Table 4. Factorial Experiment.

Test	**Factors**			**Response**
	$\boldsymbol{V}$	$\boldsymbol{T_c}$	$\boldsymbol{T_h}$	$\dot{\mathbf{Q}}$ (W)
1	-1	-1	-1	0.287
2	+1	-1	-1	0.120
3	-1	+1	-1	0.173
4	+1	+1	-1	0.013
5	-1	-1	+1	0.418
6	+1	-1	+1	0.126
7	-1	+1	+1	0.195
8	+1	+1	+1	0.098
9	-1	-1	-1	0.165
10	+1	-1	-1	0.110
11	-1	+1	-1	0.237
12	+1	+1	-1	0.056
13	-1	-1	+1	0.316
14	+1	-1	+1	0.189
15	-1	+1	+1	0.239
16	+1	+1	+1	0.219

3.2.1 Main Effects and Interaction Effects

With the results obtained for heat transfer rate, the calculation of interaction between the factors of the 2^3 factorial design was performed. The results obtained from the 2^3 factorial experiment are presented with the average values, effects of each individual factor, and interaction effects between factors, including the respective error, obtained through Origin software (OriginPro), as shown in Table 5.

Table 5. Average heat transfer rate and effects, with experimental error.

Average global of $\dot{Q}$ (W)**:** 0.185 ±0.014						
Main effects:			**Interaction effects:**			
$\boldsymbol{V}$	$\boldsymbol{T_c}$	$\boldsymbol{T_h}$	$\boldsymbol{VT_c}$	$\boldsymbol{VT_h}$	$\boldsymbol{T_cT_h}$	$\boldsymbol{VT_cT_h}$
-0.069 ± 0.014	-0.031 ± 0.014	0.040 ± 0.014	0.011 ± 0.014	0.002 ± 0.014	-0.006 ± 0.014	0.026 ± 0.014

Using a bar chart, the standardized effects were represented, that is, the absolute value of each effect divided by the error, as shown in Figure 5. It was observed that the largest effect on the heat transfer rate is produced by the volume collected in the faucet, followed by the selected temperatures in the module T_h and T_c, respectively.

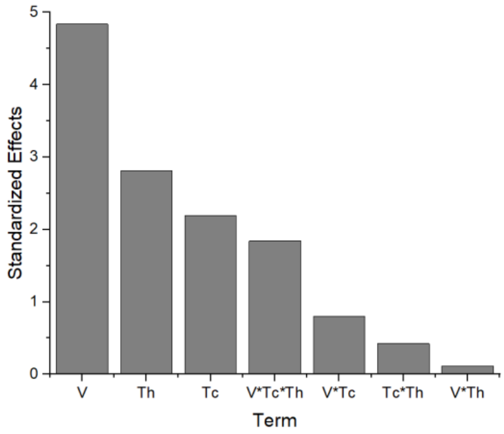

Figure 5. Standardized effects.

3.2.2 Statistical Model

When the value of the error for any of the main effects or the error of interaction between factors is greater than the magnitude of the effect itself, statistically, this effect can be ignored. According to Table 5, this is the case for all interaction effects, except for the VT_cT_h effect. Thus, the statistical model for the 2^3 factorial experiment for the heat transfer rate, $\dot{Q}_m$ [W], is given by:

$$\dot{Q}_m = 0.185(\pm 0.014) - 0.069(\pm 0.014)V + 0.040(\pm 0.014)T_h - 0.031(\pm 0.014)T_c + 0.026(\pm 0.014)VT_cT_h \quad (2)$$

where V, T_h and T_c are the coded factors.

The main effects of the three factors, when considered individually, are presented in the graphs of Figure 6. The separate analysis of these effects shows us how each level of each factor behaves, with factor V having the greatest effect on the change in $\dot{Q}$.

The main effects V, T_c and T_h, cannot be interpreted separately, as the interaction effect VT_cT_h is significant. For the joint analysis of the effects, a diagram in the form of a cube, as shown in Figure 7, is used, containing the average responses of heat transfer rate, $\dot{Q}$, which are located at each vertex of the cube. The base of the cube represents the factors T_c and T_h, while the height is represented by the factor V. All factors vary between the minimum and maximum limits, that is, from -1 to 1. The graph was also developed with the assistance of Origin software (OriginPro).

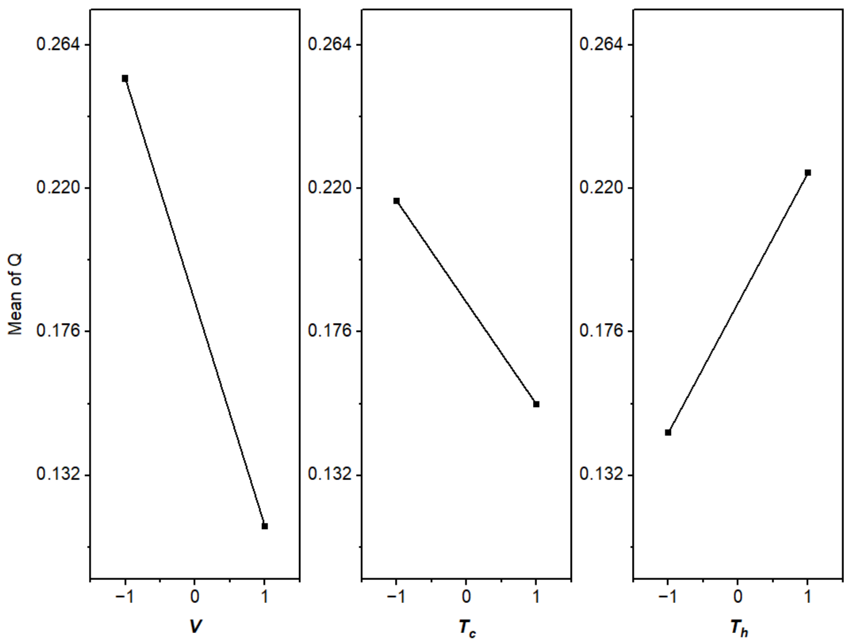

Figure 6. Main effects.

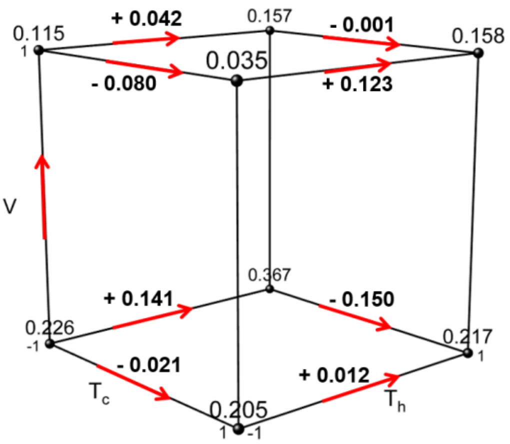

Figure 7. Cube plot of $\dot{Q}$.

Initially, analyzing the base of the cube, where V = 300 ml (-1), it can be observed that: i) when T_h was varied from 86°C to 99°C (-1 to +1), there was an increase in $\dot{Q}$, with a more significant effect for T_c= 3°C (-1); ii) when T_c as varied from 3°C to 10°C (-1 to +1), there was a reduction in $\dot{Q}$, with a more significant effect for T_h = 99°C (+1).

Next, analyzing the top of the cube, where V = 1000 ml (+1), it can be noticed that: i) when T_h is increased from 86°C to 99°C (-1 to +1), there is an increase in $\dot{Q}$ particularly significant for T_c = 10°C (+1); ii) when T_c is increased from 3°C to 10°C (-1 to +1), there is a reduction in $\dot{Q}$, but more significant for T_h = 86°C (-1).

By analyzing the heat transfer rate values for V = 1000 ml, it is evident that the variation of T_c from 3°C to 10°C (-1 to +1) practically did not influence $\dot{Q}$ for T_h = 99°C and had very little influence for T_h = 86°C. However, for V = 300 ml, it is noticeable that the change in T_c significantly affected the variation in $\dot{Q}$ for T_h = 99°C compared to T_h= 86°C.

With the diagram in Figure 7, it can be concluded that the variations in $\dot{Q}$ are greater for a smaller volume (300 ml) because initially, the hose and the faucet are cooler when they meet the hot water from the module, resulting in a greater heat transfer in the initial moments of the hot water flow. The trend for the larger volume (1000 ml) is for the initial variations to dissipate over time, as the hose and the faucet heat up quickly, reducing the heat transfer rate.

4. CONCLUSIONS

With the experimental study of the coupled module-faucet system, it was possible to identify the factors that most affect heat transfer. It was found that the combination of temperatures set in the module does not have a significant influence, which means that configuring the product with a temperature of 99°C for hot purified water and 3°C for cold water will not cause a noticeable temperature loss in the outlet of the hot purified water.

We found that the volume of hot water extracted from the product affects the outlet temperature at the faucet. For volumes below 300 ml, there was a higher heat transfer in the system because the path through which the water flows is initially at a colder temperature. For larger volumes, the heat transfer becomes smaller because the system is already heated after the initial moments of flow. One suggestion to extract smaller volumes at a temperature very close to the programmed value in the module is to use thermal insulation for the hose through which the water flows from the module to the faucet. This would allow the system to lose less heat from the hose to the environment, or alternatively, replace the material of the hose with a material of lower thermal conductivity.

In the experiments, it was observed that for larger volumes of hot water extraction, the system took more time to reestablish the programmed values, which would hinder consecutive use for larger-scale applications due to the waiting time to obtain water at the desired temperature. It was evident at the faucet that water from the supply network represents a potential source of heat loss in the system.

5. ACKNOWLEDGEMENTS

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