Higher-Level Experimental Prototype of a Control Device for Dynamic Beverage-Cooling Process

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***Summary* - In this paper development and testing of an electronic controller for operation of a beverage cooling device is described. This development is a part of a project research that includes a cooling device with a water-submerged evaporator and its adequate regulation system. Authors have developed a controller device, mathematical models, and algorithms "from scratch" and in this paper an optimization of a regulation device is described: selection of a smaller and more effective microprocessor, necessary reduction in number of inputs and outputs, new ECB development and an optimized algorithm for the dynamic cooling process.**

Keywords - beverage cooling, control device prototype, electronic controller, electronic circuit board

I. Introduction

Cooling system with water-submerged evaporator uses a concept of direct evaporation of the refrigerant on the evaporator coils, thus avoiding additional heat losses. In this type of cooling a total heat transfer coefficient is increased, as is the cooling capacity, when compared to standard cooling systems, such as air evaporator cooling systems. When circulating beverages are being cooled dynamically these advantages come in hand, since water-submerged system provides more direct cooling: heat is being transferred from liquid to liquid, and intermediate heat losses are being reduced to a minimum.

IRI2 project (with reference code KK.01.2.1.02.0036) team in its experimental phase proposed, developed, and tested a mechanical design solution comprising of water-submerged cylindrical evaporator prototype, as described in [1], [2], [3]. Additionally, a developed cooling system has fixed speed condenser fan, compressor with implemented speed control and several operating solenoid valves for refrigerant flow control. Refrigerant used for cooling is R290, which is ecologically acceptable with higher rate of energy efficiency compared to standard refrigerants.

In further development of a prototype from the mechanical and thermal perspective number of solenoid valves was reduced to three: one on the suction side, one for the oil recharge, and a bypass valve for prevention of pipe frosting. Cooling system elements (compressor, evaporator, condenser, control unit) were repositioned to make a more compact layout (fig.1) and an adequate housing was manufactured.

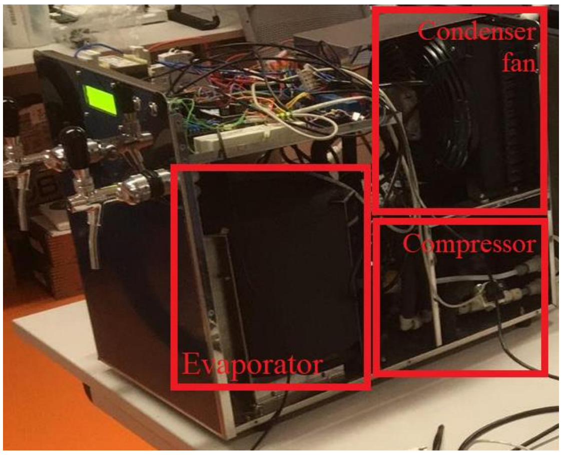

Figure 1. Final prototype of a beverage-cooling system with water-submerged evaporator

With these changes a needed progress towards commercialized unit was made, and only a development of a control system remained [4]. Control system adjustment was done accordingly with changes in mechanical and thermal element disposition.

II. Control system for a higher level beverage-cooling prototype with water-submerged evaporator

In the industrial research phase, a reduction of several input and output elements was made for the purpose of better unit commercialization and more compact element layout. Also, a simpler control unit was made, with main change in selection of a microprocessor unit. Since a reduction in number of signals and actuators was made, a simpler microprocessor unit was selected and with it a new circuit board project for was designed. Subsequently, a new ECB was made that was compatible with new microprocessor unit and external I/O elements.

A. *Sensors –input signals*

In an experimental phase prototype several sensors for pressure, temperature and liquid flow signals were installed. Pressure sensors were used for refrigerant pressure measurement on evaporator and condenser side. Temperature and liquid flow sensors were used for measurement of beverage state, with option for feedback control of a cooling system according to temperature. Pressure sensors were connected to evaporator's and condenser's pipeline entry points.

In industrial phase prototype pressure sensors have remained, and are used for control of condenser fan and compressor speed. From the beverage side, two different flow sensors are used for monitoring of two separate cooled beverages' flows, thus making an enhancement by adding a second cooled beverage pipeline.

Inputs have been assigned to its numbered connector pins, soldered on a new ECB. Assigned pin numbers are shown in Table I.

B. *Actuators – output signals*

For an adequate operation of a higher-level prototype's cooling system SSR relays are selected as actuating devices for compressor and condenser fan. SSR relays are more reliable than standard electromechanical contactors (used in previous prototype level) and are "noise-free". Four additional relays for solenoid valves have remained from previous prototype structure, with three mandatory for cooling operation: suction valve, bypass pipeline valve and oil drain valve.

Outputs have been assigned to its numbered connector pins, soldered on a new ECB. Assigned pin numbers are shown in Table I.

TABLE I. INPUT/OUTPUT SYSTEM FOR HIGHER-LEVEL PROTOTYPE

Type	*Manufacturer*	*Model*	*Range*	*El. signal*	*Pin address (STM32 ECB)*
Flow sensor 1	Digmesa AG	938-2540/01	0.041 ÷ 15 l/min	236 pulse/l	X13
Flow sensor 2	Digmesa AG	938-2540/01	0.041 ÷ 15 l/min	236 pulse/l	X14
Pressure sensor	Emerson	PT5N-30M	0 ÷ 30 bar	4 ÷ 20 mA	X16
Pressure sensor	Emerson	PT5N-07M	-0.8 ÷ 7 bar	4 ÷ 20 mA	X15
Solenoid valve 1	Castel	CM2 9110/RA2	OFF/ON	0/24VAC	X53
Solenoid valve 2	Castel	CM2 9110/RA2	OFF/ON	0/24 VAC	X56
Solenoid valve 3	Castel	CM2 9110/RA2	OFF/ON	0/24 VAC	X54
Solenoid valve 4 - optional	-	-	OFF/ON	0/24 VAC	X57
Compressor	SECOP	NLV12.6CN	40 ÷ 155 Hz	2000÷4500 rpm	X59
Condenser fan	ELCO	VNT 12/20 334	OFF/ON	0 ÷ 230 VAC	X58

C. *Hardware interface*

After analysis of the lower level prototype, it was necessary to make certain improvements on the circuits and on the program support of the microcontroller. The optimization included new selection of microcontroller and SSR relays that control main cooling elements on the device. Due to reduced number of analog/digital I/O, the main change compared to the lower-level prototype is the replacement of the microcontroller. New unit is from the same series (fig. 2) – *"Blue Pill"* STM32F103C8T6.

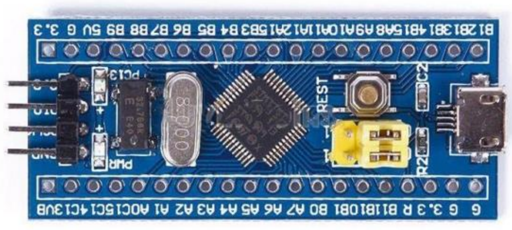

Figure 2. Microprocessor unit "Blue Pill" STM32F103C8T6

In the previous phase of the development project, three different transmitters were connected to a control system of a prototype: temperature and pressure sensors' MBED transmitter, flow sensor's MBED transmitter, and frequency control MBED transmitter [1]. However, due to the reduction requirements of an electronic device (spatially and in I/O number) a new ECB was designed and made to accommodate new microprocessor unit and I/O connector kits. On fig 3. a block schematic of a new control system is shown.

The signals are 4÷20mA current loop pressure sensors P1 and P2, and a PWM type flow control sensors F1 and F2 shown on fig. 3. Their appropriate signals are converted into digital form [5] and are displayed locally on the LCD display of a device, shown on fig. 4.

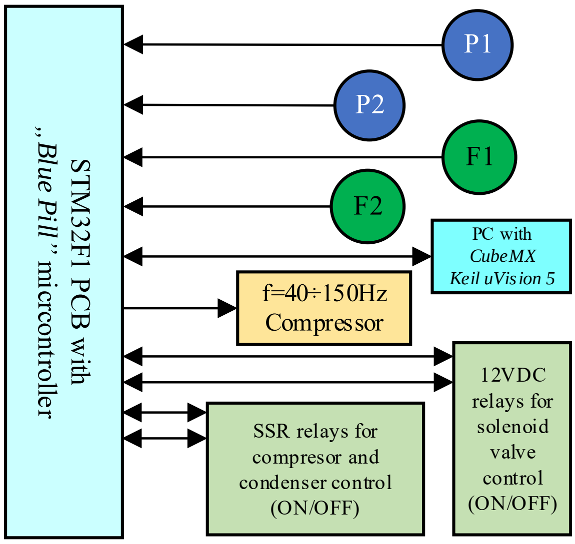

Figure 3. Block schematic of a higher-level prototype's control system

Figure 4. LCD display on a front panel of a prototype

D. ECB design for a higher level prototype

Compact control device development phase had a goal of eliminating unreliable connections and raising the reliability of the control system. Soldering of contacts and shielding the lower-level analog signals managed to eliminate these physical flaws. A printed circuit board, that would be used to connect microprocessor unit and all the necessary sensors and actuators was made as a result of ECB development phase. Requirements for this development phase were:

- the NUCLEO STM32F103C8T6 microprocessor control unit [6] is connected to the main ECB by a strip connector for modular attachment or detachment,
- output for main elements is done with external SSR relays, while output for valves is done with relays soldered on the board,
- the connection of external elements is done with soldered terminal blocks,
- 12 VDC power supply is derived with required voltage levels for all circuits,
- external LCD display is connected via I2C protocol to appropriate connector, and it is mounted on the housing of the prototype [7].

The ECB (fig. 5) and the schematic (shown on fig. 6) were designed via Autodesk EAGLE CAD tool. The ECB is double-sided. Connecting traces are laid out on both sides of the ECB and it is designed in THT technology with no SMD components for surface mounting, as was done with ECB in previous phase of experimental research.

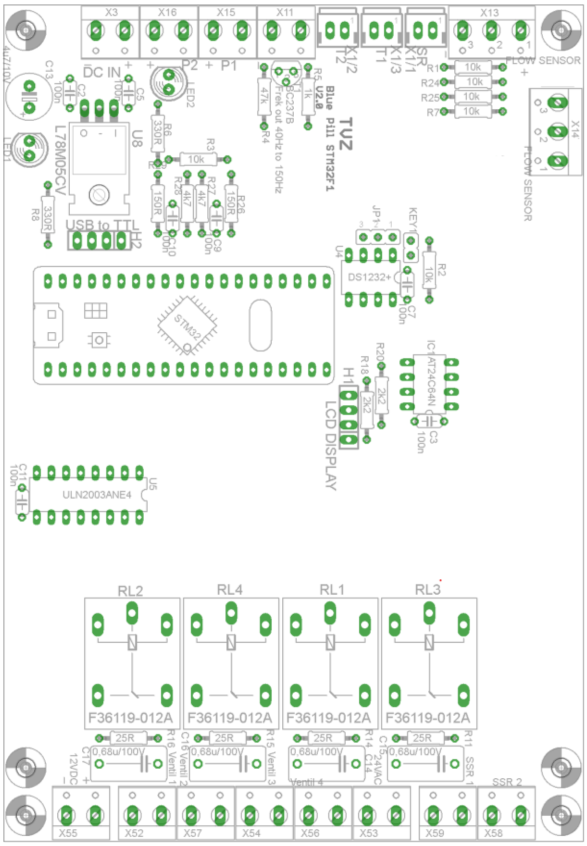

Figure 5. ECB design layout for control system

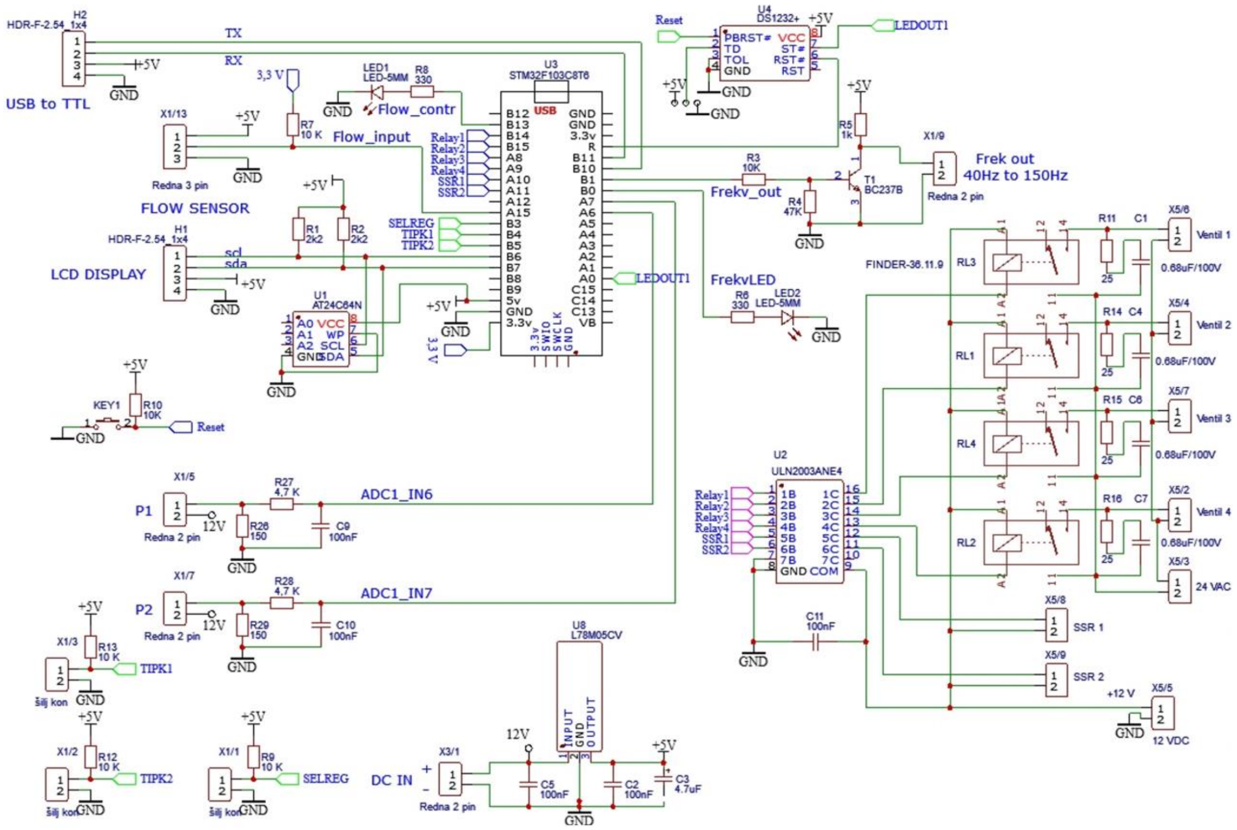

Figure 6. Detailed schematic of a ECB for higher-level prototype's control system

E. *Control concept and code development for control*

For control reference a temperature is selected. Since there are no temperature probes in the system, a temperature is obtained through pressure measurement since it is directly linked to a pressure of the refrigerant [8]. Scaling of the temperature is non-linear and it is described by a fourth order model, depending solely on the thermodynamical analysis of the refrigerant. The scaling equation is as follows:

$$\begin{aligned} p(T) = -27.2037 + 0.35656 \cdot T \\ - 1.29068 \cdot 10^{-3} \cdot T^2 \\ - 5.5771 \cdot 10^{-7} \cdot T^3 \\ + 7.58418 \cdot 10^{-9} \cdot T^4 \end{aligned} \quad (1)$$

Control concept (and its appropriate code) is divided into two different parts:

1. Beverage flow hold – preparation state, and
2. Beverage flow state.

In the first part a concept for regulation includes dead-zone band for temperature maintenance of a static or quasi-static state of beverage, where no flow or very slow flow is being implemented. A discontinuous type of regulation is needed in this static environment, due to possibility of pipeline freezing if a continuous type is being used. In the second part, a continuous PI regulation type is implemented. While a flow of the beverage is above a limit defined for the static state, the continuous concept takes place, and a frequency of the compressor is being regulated according to the temperature/pressure setpoint.

Package *Keil uVision5*, along with *"Blue Pill"* microcontroller, enables project management, source code editing, and targeted microcontroller code loading and execution. Module *uVision Debugger* is used for code optimization of the applied application. With an integrated ST-LINK USB on the "Blue Pill" microcontroller, debugging and code manipulation is simple to implement. Software interfaces *STM32CubeMX* and *Keil uVision5* with *Keil C-compiler* use a layer labeled HAL (*Hardware Abstraction Layer*) that connects the microcontroller software libraries and applications in one project. Direct approach to measurements is also provided to these instances via excel add-in *Data Streamer*. With this add-in, acquisition is made simpler than the one used in previous research phase, because a smaller set of real-time data. A MATLAB/Simulink environment [9] is no longer needed and has been discarded in this phase.

F. *Control system placement in a device prototype*

Control system, along with its actuators is placed on top side of a device prototype. An inox tray is designed to accommodate developed ECB with microprocessor, DC power supplies (for SSR's and ECB power input), actuating devices, transformer (solenoid valves' power supply) and protection devices. Disposition of elements placed on a tray is shown in fig. 7. Tray with elements has adequate dimensions, for an outer housing to be finely adjusted so whole device can be covered appropriately.

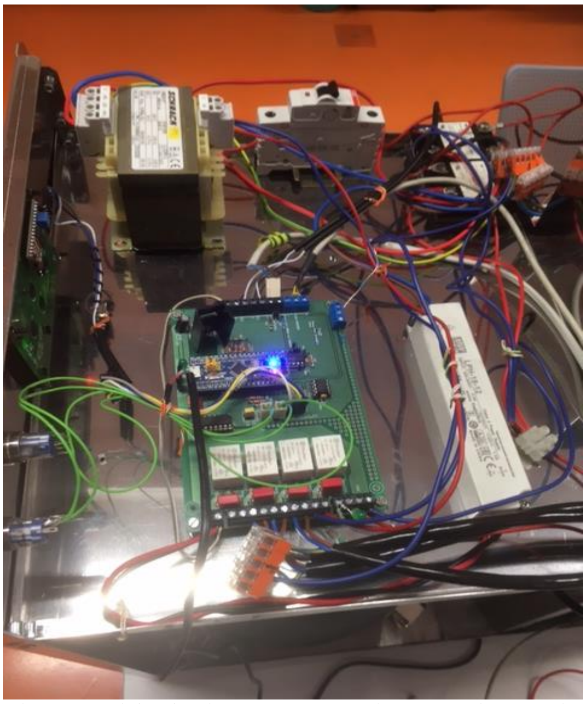

Figure 7. Higher-level prototype's control system – placement in housing

III. CONTROL SYSTEM'S PERFORMANCE – TESTING RESULTS

For the purposes of testing the prototype and a control system, a heating system for preparing test liquid has been installed. This system consists of water (testing liquid) tank, electric heater module and a simple dead-zone controller for switching the heater according to desired temperature of the liquid that is to be prepared for testing. The heating/preparation system is shown on fig. 8.

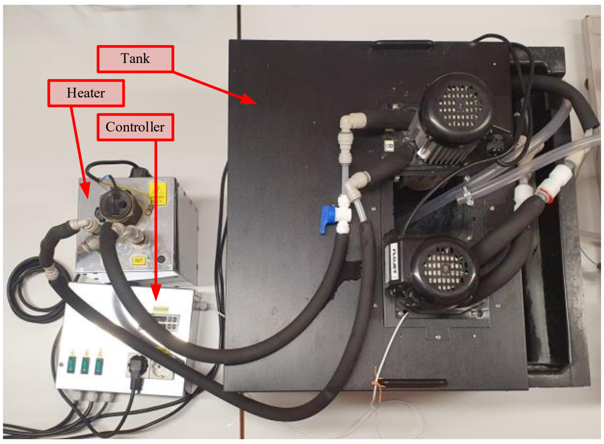

Figure 8. Heating system for preparation of testing liquid

Testing was done for different liquid flows, with subsequent stop of liquid after a tap is opened for some time. Values that are being observed are cooled liquid flow/stop, refrigerant pressures, temperature setpoint, compressor's drive frequency and compressor switching state. Four different cases were observed:

1. Test case with no liquid flow
2. Test case with liquid flow equal to 0.44 l/min,

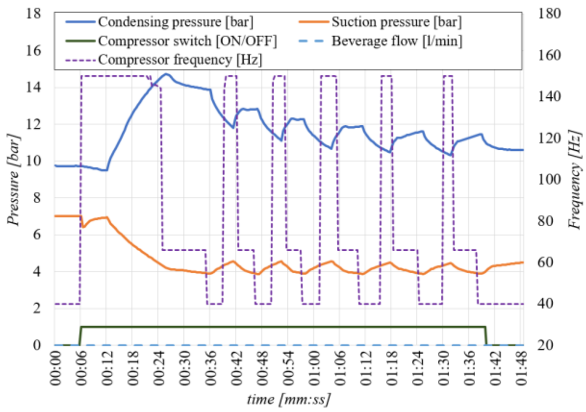

Figure 9. Test case 1 – cooling the beverage in preparation state with no flow

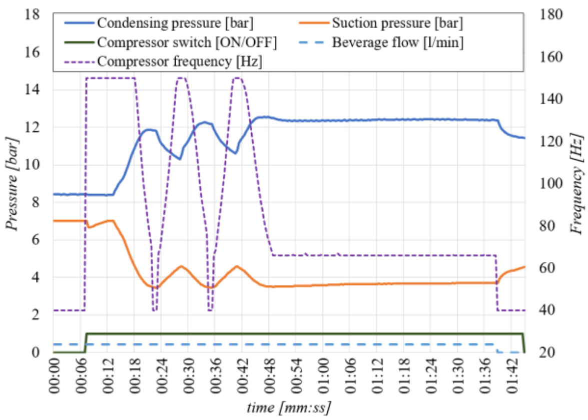

Figure 10. Test case 2 – cooling the beverage, flow of 0.44 l/min

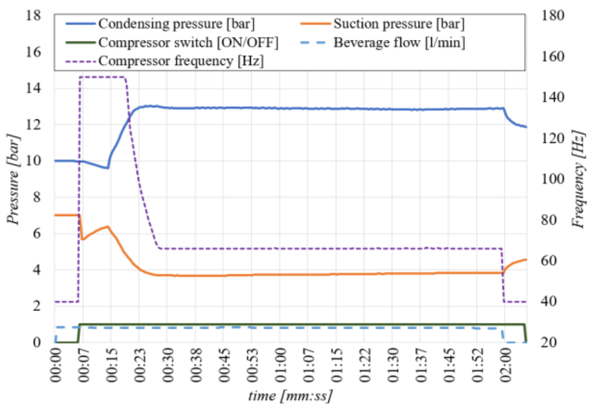

Figure 11. Test case 3 – cooling the beverage, flow of 0.82 l/min

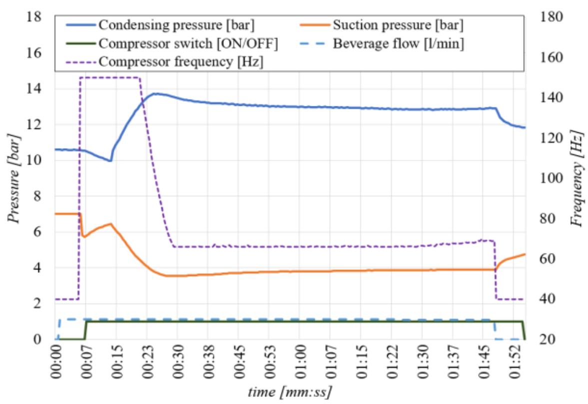

Figure 12. Test case 4 – cooling the beverage, flow of 1.12 l/min

3. Test case with liquid flow equal to 0.82 l/min,
4. Test case with liquid flow equal to 1.12 l/min.

In all four cases a test beverage temperature of 3°C corresponds to suction pressure of 3.9 bar of a refrigerant. Results from measurements are shown on fig. 9 to fig. 12, for described test cases, respectively.

Linear regulation of compressor's motor speed is accustomed to frequency range from 66 Hz to 150 Hz, and below 50 Hz compressor stops. Between 50 and 66 Hz compressor's motor runs at minimum speed. Control curve characteristic is shown on fig. 13.

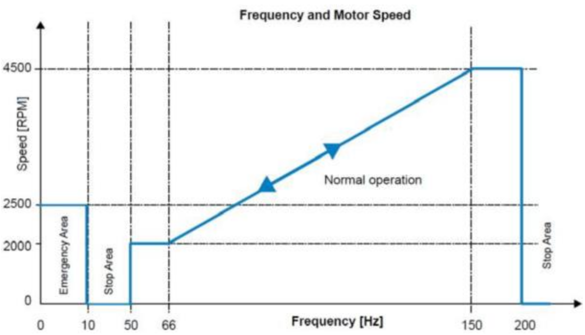

Figure 13. Frequency vs. speed characteristic for compressor control [10]

While compressor reaches its operating point it runs at minimum speed, until a preprogrammed delay for minimum compressor on time elapses. This delay is implemented so the compressor doesn't switch off too soon. This compressor's behavior can be observed in all four cases. Compressor switch state observes the switching state of the SSR relay of the compressor, and with it a suction solenoid valve. This state is not to be confused with actual state of the motor speed of the compressor which may reach a 0 rpm, when a 40 Hz frequency state occurs, when still a suction solenoid valve is opened.

In the first case, a dead-zone type regulation is applied, and this occurs in a repeated switching of the compressor. These 40 Hz switching states occur in lesser numbers once a refrigerant (and beverage) reaches its desired temperature/pressure. In the second case, when a reduced beverage flow is applied, a compressor also repeatedly switches, but with continuous type of pressure regulation. This behavior is a consequence of a compressor strong enough to endure faster exchange of beverage. In more static environment it reaches operating point much sooner with an undershoot of pressure as a consequence. This causes a compressor to switch from 0 to 1500 rpm repeatedly until a desired pressure is reached without an undershoot.

In the tests 3 and 4 operating point is reached quickly (during a "first glass pouring") and with only one peak of speed at 1500 rpm, after which a fine continuous regulation takes place. No undershoots of suction pressure are present, as well as no repeated compressor switching. In conclusion, this observation acknowledges the correct choice of the compressor for the appropriate dynamic operation of the cooling beverage tap device, while adequately enduring dynamic thermal load of a beverage flowing.

IV. Conclusion

In the experimental research phase for the tap device prototype with water-submerged evaporator a control algorithm with various measurements and actuators was implemented, tested, and described in [1], [2], [3]. This phase was a waypoint for observing the commercial aspect of the project. Since a more aesthetic and practical product needed to be made for possible successful commercial launch, a mechanical, electrical, and automatic control elements were reduced spatially and numerically.

In the industrial research project phase following changes were made:

- device prototype gained a new look: it was more compact in size and more acceptable for transport,
- all parts of the power supply and automatic control systems were adequately placed on a tray designed for such a purpose, and for easy access for the device maintenance personnel,
- direct temperature control with pressure monitoring was replaced with more appropriate pressure control (better response time, smaller number of sensors),
- a new microcontroller unit was selected, lesser in size and in number of ports, and with adequate performance,
- a new ECB was made to optimally accommodate microcontroller, actuators and connecting pins,
- a new control program was implemented for the final control solution that corresponds to described changes in the device,
- functionality of the device was tested with satisfactory results.

As a result, following goals of the industrial research phase were achieved: more compact device was made with lesser potential expenses for the commercial product manufacturing process and a simpler use of the device for the end-user is provided.

V. References

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