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ON THE DEVELOPMENT OF A TECHNOLOGICAL SOLUTION TO MITIGATE SUMMER MORTALITY IN BRAZILIAN OYSTERS' CROPS: AN APPROACH TOWARDS A HRS BASED APPLICATION

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Abstract. *The search of a technological solution to provide a controlled environment able to inhibit the spawning in farmed oysters, and so to avoid the phenomenon known as summer mortality, indicates the hydraulic refrigeration system as a possible outcome. Being de entrainment process of a gas in a water descending stream a key factor for the design of such a system, this article aims to explore the experimental results of an hydraulic air compressor test rig, built for this purpose. The pressure in the compressor chamber, as well as the water and air flow rates, were measured and compared to mathematical models available in the literature. The results suggest that, although promising in achieving condensation pressures for some commercial refrigerants, the design of the entrainer of vital importance to assure the desired gas mass flow in such applications.*

Keywords: *product development, water temperature, oyster farming, refrigeration system.*

1. INTRODUCTION

The state of Santa Catarina, major producer of farmed oysters in Brazil, has impressive conditions for oysters farming. The specie farmed in Santa Catarina´s coast is original from the Pacific Ocean, where usually low water temperatures prevail (MPA, 2016; Mizuta, *et al., 2012*). Even though local water temperatures are favorable most of the year, it is during summer that they raise up to 30ºC, inducing the crops to severe weight loss and death rates (Garcia, *et al., 2016*).

Bivalve mollusc farming is a branch of the mariculture, namely the aquaculture division dedicated to the cultivation of marine organisms for food and other sea products. The mariculture in Brazil is predominantly oriented towards shrimp farming with greater relevance in northeastern Brazil, and the bivalve mollusc farming, which is found almost exclusively in the southern Brazilian state of Santa Catarina. With an annual production exceeding 18,000 tons, the state now accounts for 95% of the national production of bivalve molluscs, with the Pacific oysters, Crassostrea gigas, as the second largest production. The oyster farming cluster of Santa Catarina is located between the towns of Palhoça, in the south, Governador Celso Ramos, in the north, and the cities of Florianopolis and São José, respectively in the west and the east (Santos, *et al., 2012*; Dorow, 2013).

Santa Catarina has impressive conditions for oysters farming: not only it does have an appropriate physical geography, but it also possesses good quality water, a convenient water temperature regime, and the abundance of nutrients brought by the ocean stream. In particular, the region of Florianopolis receives the up surged waters coming from the South Atlantic Central Water stream (SACW), whose predominant features are the average temperature of 17ºC and a salinity of 35%, with the influence of the plume of the Prata River as a source of nutrients and chlorophyll

(Mizuta, et al., 2012). The specie farmed in Santa Catarina´s coast, Crassostrea gigas, is original from the Pacific Ocean, where usually prevail low water temperature ranges. The mollusc is well adapted to the coastal environmental conditions, where the combination between excellent water temperature ranges and an appropriate geographic location, allow the local producers to harvest the oysters once a year, at least. Even though water temperatures are considered to be excellent most of the year, it is during the summer season that they raise up to 30ºC. Such condition is unknown to the Crassostrea gigas that reacts by starting a frenetic reproductive process, leading to high levels of stress, excessive weight loss and death rates up to 30% (Silveira Jr., *et al*., 2008; Silveira Jr., 2010).

When reproduction begins, the animal uses its glycogen reserves for the production of gametes. Glycogen is identified as having a central role in directing the energy reserves to the vital activities of the oyster. Spawning is a highly energetic demanding process which imposes a significant weight loss and highlights the immunodeficiency, what may increase the death rates [11]. After spawning the Crassostrea gigas presents very low levels of glycogen, which explains its fragility to react against adverse conditions such as thermal shock and biological attacks, since the reaction to these situations requires the same reserve of glycogen already spent in the reproduction process. According to literature, if the spawning process is not triggered, a substantial reduction in the mortality rates can be achieved (Garcia, *et al*., 2016). Such finding justifies the synthesis of a technological solution, a process that can benefit from the application of product development methodologies. The above scenario points to an opportunity for scientific and technological research, and it is remarkably important to the Brazilian aquaculture cluster.

This article presents results subsequent to those described in recent work (Garcia, *et al., 2016*), and has focus on tests results from a hydraulic compressor designed to obtain information on the entrainment process of a gas in a descending water column. Understanding this process in detail is fundamental for the design of a hydraulic refrigeration system (HRS) (Rice, *et al., 1981*), which corresponds to one of the identified alternative solutions in the conceptual phase, as per the adopted technical system development methodology.

2. LITERATURE REVIEW

In this section, the themes that gave rise, as well as those that guide the development of this research, are object of literature review. The search for solutions to the presented problem was conducted through the product development methodology described by Back *et al.* (2008), emphasizing the results obtained in the informational and conceptual phases. The conceptual phase of the project revealed that the refrigeration technology has predominant relevance for the viability of any proposed solution. Since the hydraulic refrigeration system is one of the proposed alternatives, the literature on hydraulic compressors will also be visited.

2.1 Product Development Methodologies

Product development is the process of converting needs and requirements of the project clients into a technical solution, considering available resources, existing constraints and the projected life cycle. As to systematize the product development process, methodological approaches help with organizing a logical sequence of phases, steps and activities. Concurrent Engineering, Stage Gates approach, and Integrated Product Development Methodology are amongst representative approaches found in literature (Andreasen and Hein, 1987; Paul and Beitz, 1988; Amaral, *et al*, 2006, Back, *et al*., 2008). In model proposed in the latter, the so called Informational Design and the Conceptual Design are the phases that deliver respectively the project specifications list and the physical principles that complies with those specifications.

The informational design phase starts from the general statement of a need or opportunity for product development, providing a list of design specifications, the target specifications list. Information gathering tools are applied on a survey regarding demands and requirements of project's clients. The project scope is stated based upon information gathered in meetings between the project team and representatives of these clients. The necessities list can be compiled after open interviews, observing (but not limited to) a common set of questions (Back, *et a*l, 2008). Such approach , which was used in this research, is suitable to obtain the most comprehensive and detailed information on the project object (Bone and Quaresma, 2005).

The identified necessities, categorized and prioritized by the application of techniques such as affinity and Mudge diagrams, are used to build the Quality Function Deployment first diagram (the "House of Quality"), in which information is appropriately organized and valued according to their relevancies, providing the necessary insight to convert qualitative raw information into a consistent set of technical design specifications (Amaral, *et al*, 2006, Back, *et al*., 2008).

The conceptual phase of the project begins after the approval of the target specifications' list and delivers, when completed, the conception of the desired technical system. Initially, the system's main function and the secondary functions are established. The functional structure of the product is then selected by the comparative analysis between several alternative structures, built upon the identified functions.

Once the functional structure to be adopted is determined, creativity techniques, as well as intuitive and systematic methods, are applied to generate solution principles for each function to be met. The combination of the different solution principles in different architectures will provide a variety of design possibilities that shall be evaluated according to the design requirements, but also by factors such as: manufacturing-related aspects, target cost, development-related risks, and security, among others. The selected design is analyzed in order to the identification of its production process, possible suppliers and applicable production technologies. The results of the phase have to be approved by the project team before starting the subsequent phases (BACK, *et al*., 2008).

One of the alternatives resulting from the conceptual phase of the project concerns the use of hydraulic compression to power a refrigeration system. This paper presents the results of tests conducted to better understanding the entrainment process of a gas in a down flow hydraulic column. In accordance to the purpose of this paper, the literature on hydraulic compressors and hydraulic cooling systems will be discussed in the next section.

2.2 Hidraulic air compressors and hidraulic refrigeration systems

The Hydraulic refrigeration systems are characterized by a descending flow water column working as the compressor and condenser for the refrigerant fluid, as shown in Fig. 1:

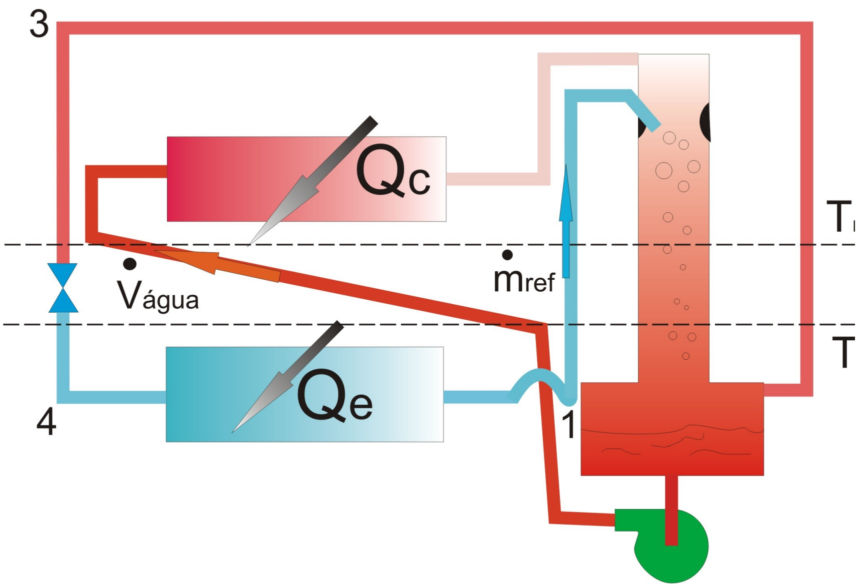


Figure 1. Hidraulic refrigeration system main components

Two closed loops that communicate in the column of compression 1 can be observed in Fig. 1: the refrigerant loop, points 1 - 3 - 4; and the water loop, in the inner part of the figure. The refrigerant flows through the circuit 1 - 3 - 4 - 1, leaving the separation tank, located in the lower part of the compression column, as sub cooled liquid, and reaching the expansion valve - 4 where its pressure and temperature are reduced to the evaporation conditions. When flowing through the evaporator, 4-1, heat - Qe - is transferred from the inner environment to the refrigerant that changes its phase and returns to the top of the compression column as superheated gas where it heat charge is captured by the downward flow of water. As refrigerant and water flows downwards the column, the static pressure rises up to the corresponding condensing pressure. In the condensation process, the fluid delivers the heat to the water, increasing substantially its temperature. When leaving the compression column, refrigerant and water are separated by density in the separation tank, closing the refrigeration circuit. The water in the separation tank is pumped back to the top of the column 1, passing through a heat exchanger and rejecting heat, Qc, to the external environment (RICE, *et al.,* 1981).

Refrigerant and water have the same temperature at each point of the compression column thus the process can be considered to be isothermal. The isothermal compression process is considered to be thermodynamically superior to the adiabatic process of conventional compressors (Rice, *et al*., 1981).

The development of the hydraulic refrigeration system has its origin in the studies on hydraulic air compressors, which were used since the middle ages in the so-called Catalan forges. Table 1 presents the main references that describe the basis of hydraulic air compressing and which had been used as theoretical support in the present research.

Table 1. Hydraulic air compression – main references

Authors	Year of publication	Contents
Taylor Hidraulic Air Compressing Co.	1897	Historical record on the use of hydraulic potential energy for the generation and supply of compressed air.
Ahrens, F.H.; Berghmans, G. A.	1978	Presents an assessment on the use of existing dams for the production and supply of compressed air for industrial applications.
French, M.J.; Widden, M. B.	2001	It analyzes the potential for additional electric power generation through the hydraulic compression of air in small height hydroelectric plants.
Aissa, W. A., *et al.*	2010	Presents a proposal for the mathematical modeling applied to the hydraulic compression of air in small manometric heights.

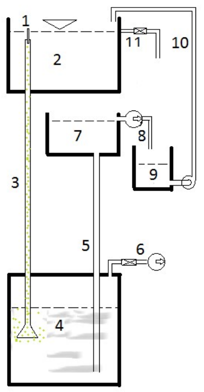
Understanding the entrainment process of a gas in a descending water column in detail is fundamental for the design of a hydraulic refrigeration system (HRS). In Equation 1 expression, adapted from the work of French and Widen (2001), the minimizing of the residuals, keeping the volumetric ratio of air to water as a variable (x), will deliver an approach to determine the volume of entrained air.

$$0 \approx -p_4 + p_1 + \rho g h_{1-4} - x_1 p_4 \times \left(\frac{\ln(p_4/p_1)}{(p_4/p_1)}\right) \tag{1}$$

Nomenclature:
- p – pressure;
- ρ – water density;
- g – gravitational constant;
- h – vertical distance;
- x – ratio of the volume of air in water.

Equation 1 considers the following assumptions:
- isothermal compression;
- constant water flow velocity in downward column;
- volumetric ratio of air in the downward column is a function of pressure.

The volumetric ratio of water is measured at position 8, whilst pressures are measured at positions 1 and 4. All indexes refer to Fig. 2.



1 – Air entrainment tube
2 – Upper reservoir
3 – Downward stream pipe
4 – Decanting chamber
5 – Upward stream pipe
6 – Pressurized air outlet
7 – Lower reservoir

Figure 2. Test rig

3. EXPERIMENTAL PROCEDURE

The test rig presented in Fig. 2 is based on that described by Aissa, *et al,.* (2010). Tanks 2 and 7 are connected to a separation chamber by tubes 3 and 5. The difference in height between them generates a flow from 2 to 7. Levels in both tanks are held constant by the overflow pipes 8 and 11, and by pumping the water collected in reservoir 9 back to 2. Air, at atmospheric pressure, is captured by the downward flow at position 1 positioned at the entrance 3. Velocity of the downward flow is reduced in chamber 4, allowing the separation of air from the liquid that goes up through pipe 5 to tank 7.

Water flow rate is measured in the overflow pipe 8. Air flow rate and pressure inside the chamber 4 are measured at the air outlet pipe 6. The measuring instruments are described in Tab. 2.

Table 2. Characteristics of the measuring instruments.

Measured parameter	Instrument	Measuring range	Measurement uncertanty
Mass (of water)	Digital scale model Filizola MC15	0 – 15 kg	0,005 kg
Time	Digital chronometer model Techos YP2151/DC453	9h, 59 m, 59 s	0,01 s
Distance	Measure tape	0 – 2 m	0,001 m

Water flow values were measured by filling of a recipient in a certain time lapse and the determination of the mass of water using the digital weight scale. Pressure was measured by reading the difference between initial and final values in the measure tape mounted in a liquid-column manometer specially designed for this experiment. Air flow rate was measured by filling a certain volume within a determined time lapse, at a known pressure. Equations 2, 3 and 4 were used to determine, respectively, water mass flow rate, air mass flow rate and the inner pressure in the reservoir 4 (see Fig. 2):

$$\dot{m}_{water} = \frac{\Delta m}{\Delta t} \quad (2)$$

$$\dot{m}_{air} = \rho_{air} * (l * d) * \frac{\Delta h}{\Delta t} \quad (3)$$

$$p_{reservoir} = p_{atm} + \rho_{water} * g * \Delta h \quad (4)$$

4. RESULTS AND DISCUSSION

Table 3 presents the results of the proposed model and those obtained by measuring the related parameters while performing the test rig.

Table 3. Estimation of the entrainment process

Pressure in the tank 4 (Pa)	Water mass flow rate (kg/s)	Air mass flow rate – measured (kg/s)	Air mass flow rate - model (kg/s)	Measured ratio of air in water	Estimated ratio of air in water
114374,64111 ± 0,00007	0,24 ± 0,01	8,080E-06 ± 0,01	8,688E-06	4,424E-02	4,682E-02

The difference in values for measured and estimated ratio of air in water is less than 6%, and de difference between the estimated and measured mass flow of air in the system is less than 8%. The measurement uncertainty for the air mass flow rate is not compatible with the measured values due to the very simple means to obtain the corresponding results.

Figure 3 presents estimated pressures in chamber 4 as a function of the distance between reservoirs 4 and 7.

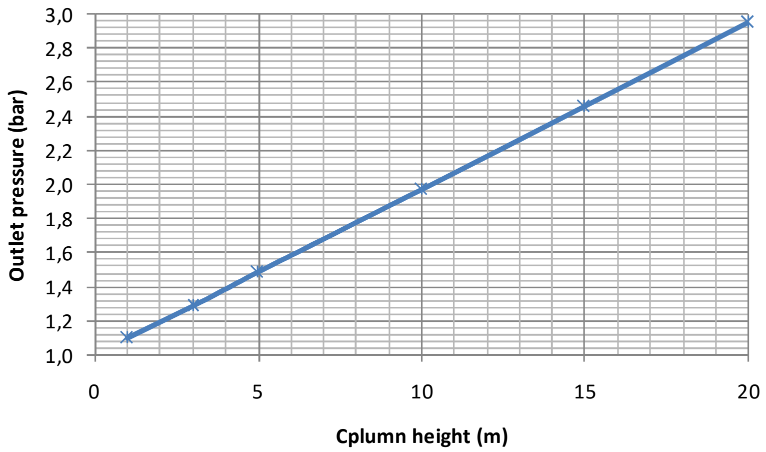


Figure 3. Estimated outlet gas pressure versus column height

5. CONCLUSIONS

Losses in the system are higher than those predicted by the model and shall be better understood. Estimations shall be confirmed in future tests, but indicate possible applications in HRS systems as the obtained values are close to the desired condensation pressures in some available commercial refrigerants. Although the model has accurately predicted the ratio of air in carried by the water column, the design of a entraining device that delivers the desired air mass flow and suitable bubble distribution and sizes had shown to be a considerable challenge for future studies.

The expected values for air mass flow rate for this size of air compressor demand more accurate and expensive instruments, which were not available for this test, but the obtained results are good enough to encourage using the model to dimensioning a bigger test rig, allowing to measure the air volumetric flow rate with a hot-wire anemometer.

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