

MODELING HEADSPACE PRESSURE IN RETORTABLE PACKAGES

By

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To both my grandfathers,  
Dr. Paluri Bhimeswara Rao and Dr. Yerrapragada Venkata Giri Satyanarayana Murti

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## LIST OF ABBREVIATIONS

CRT	Constant Retort Temperature
DAQ	Data Acquisition System
EHEDG	European Hygiene Engineering and Design Group
FDA	Food and Drug Administration
MIG	Mercury in Glass
IAPWS	International Association for the Properties of Water and Steam
USDA	United States Department of Agriculture
VRT	Variable Retort Temperature

Abstract of Thesis Presented to the Graduate School  
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## MODELING HEADSPACE PRESSURE IN RETORTABLE PACKAGES

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Flexible packages, a new attraction in the market for shelf-stable canned foods, are more susceptible to damage during thermal processing for sterilization. In order to maintain the integrity of the package, it is important to keep the pressure differential across the package walls at a minimum. In this study, experiments were carried out to predict internal pressure in the headspace of a rigid pressure-tight module that withstood variations in temperatures and pressures. A stainless steel module was custom-made with a reseal-able lid, provisions for thermocouples, an inlet valve from which to pull vacuum, and a dial gauge to measure headspace pressure. The module was instrumented so as to measure and record the temperature profile at two different locations, one near the top and one near the bottom of the module, while undergoing thermal processing in a retort. For each set of experiments, three food systems were used to fill the module; pure distilled water, saline solution (5%) and sucrose solution (10%). A mathematical model was used to predict the headspace pressure profile in response to two experimentally measured temperature profiles (near the top and bottom). Results from these studies were compared with results from earlier work to

account for the error between experimental and predicted headspace pressure profiles found in that work. This will lead to better control and knowledge of overpressures required during thermal processing to minimize differential pressure, thus avoiding damage to the flexible packaging and maintaining the quality and safety of food. Results showed that differences between predicted pressures from top and bottom temperatures and differences between measured and predicted pressures found in the previous work followed similar patterns and were of the same order of magnitude. These findings supported the hypothesis that disagreement between measured and predicted pressures found in the previous work was likely due to the reason that the temperatures used to predict pressures were measured at the bottom of the module, while the measured pressure was generated in response to head space temperature at the top of the module.

## CHAPTER 1 INTRODUCTION

### **Background and Justification**

The technology of packaging food in cans, jars and other rigid containers now has to compete greatly with shelf stable foods in flexible packages. Flexible packages offer the advantages of lower storage space and lighter weight as compared to rigid glass or metal containers, which are hard and heavy. They may be in the form of wraps, bags, pouches and sacks. An important attribute of flexible packaging is its ability to form thinner, lighter, more compact packages (Selke et al., 2001). Products in flexible packages require significantly less heating time to achieve commercial sterility. Thus, such products are fresher, superior in quality and require lower processing cost (Brody, 2002). While being processed under high temperature and high pressure conditions in the retort, the flexible package may suffer damage to its walls and seal. Due to its delicate nature, careful control of overriding air pressure is needed during retort processing.

During thermal processing in the retort, internal pressure is built-up in the headspace of sealed packages. This internal pressure is caused by internal water vapor and entrapped gases expanding in response to increasing temperature. At high temperatures, the solubility of gases in the solution decreases and they are released into the headspace of the package. The entrapped gases in the headspace consist primarily of the released gases and residual air after vacuum. This internal pressure may be greater than the saturation pressure of the steam in the retort. If the internal pressure is greater, the package may swell or burst, and if it is lesser, the package will indent or collapse. The increasing internal pressure in a flexible package must be

continuously counterbalanced by providing external pressure. This external pressure can be provided by the introduction of compressed air along with saturated steam in the retort.

The delicate nature of a flexible package undergoing thermal processing requires precise control of overriding air pressures, and is of critical importance. In order to keep the pressure differential across the package at a minimum, internal pressures must be known or estimated. In most cases, a trial and error approach is followed to determine optimum overriding air pressures. Mathematical modeling of internal headspace pressure could reduce this element of uncertainty as well as time and cost, thus, becoming a useful tool to predict optimal overriding air pressures during thermal processing. The quest for such models has been the subject of much previous work.

### **Previous Work**

Chen et al. (2004) developed a means to choose a reasonable temperature profile for processing, called multiple ramp variable retort temperature control (VRT). Alternately, a constant retort temperature (CRT) approach by Salgado et al. (2011) or Chen et al. (2002) could be adapted to save process times and preserve quality of food. Various methods to control retort temperatures are real-time data acquisition, on-line correction factors, mathematical heat-transfer models described in the work by Simpson et al. (2007) and Teixeira et al. (1997). However, these studies do not address the damage caused on the package wall and seal due to internal pressures built-up in the headspace of the package.

Pascal et al. (2002) addressed the effects of the pressure differential on seal strength and sensitivity of package wall to changes in headspace volume. But,

predictions of pressures inside the package that raised concerns of seal strength and package wall sensitivity were not made.

Ghai et al. (2011) attempted to develop a mathematical model to predict internal pressure in the headspace of a rigid pressure tight module during thermal processing. This model predicted internal headspace pressure in response to the temperature of the product under specified initial and final conditions. The equation of the International Association for the Properties of Water and Steam (IAPWS) was used to estimate vapor pressure of water and was coupled with Raoult's Law for saline and sucrose solutions. The Ideal Gas Law served as basis for estimating headspace pressure caused by expansion of non-condensable gases as a function of temperature and specified initial and boundary conditions. Results from this work revealed some disagreement between predicted and measured pressures during retort come-up time as can be seen in figures 1-1, 1-2, 1-3 for distilled water, saline solution (5%) and sucrose solution (10%). Moreover, in the case of saline solution (5%), experimentally measured pressure profile appeared as a ramp of increasing pressure over time. This was attributed to the likelihood that Aluminum in the construction material of the module reacted with salt inside the module producing Hydrogen gas. This gas increased internal pressure over time, and could not be accounted for in the mathematical model.

One hypothesis proposed in our study was that the disagreement between the measured and predicted pressures by Ghai et al. (2011) in the case of saline solution could be due to the material (Aluminum) from which the module was fabricated.

A second hypothesis was that the disagreement during retort come up time was caused by the positioning of the temperature sensor (bottom of the module), while pressure buildup was driven by temperature in the headspace at the top of the module.

### **Objectives**

The objectives of this work were to do the following:

1. Arrange for design, fabrication and testing of a new pressure-tight module with which to measure and record internal temperature profiles at the top and bottom of the module while it underwent thermal processing in a retort. The new module was fabricated to the same shape and dimensions as that used by Ghai et al. (2011), but with Stainless Steel.
2. Measure and record temperatures at two different locations inside the module (top and bottom) during thermal processing runs in the retort for each of three food systems; pure distilled water, saline solution (5%), and, sucrose solution (10%).
3. Predict internal pressure profiles in response to the top and bottom temperature profiles using the mathematical model developed by Ghai et al. (2011).
4. Compare the difference in pressure profiles predicted from the top and bottom temperature profiles with differences between predicted and measured profiles reported by Ghai et al. (2011).

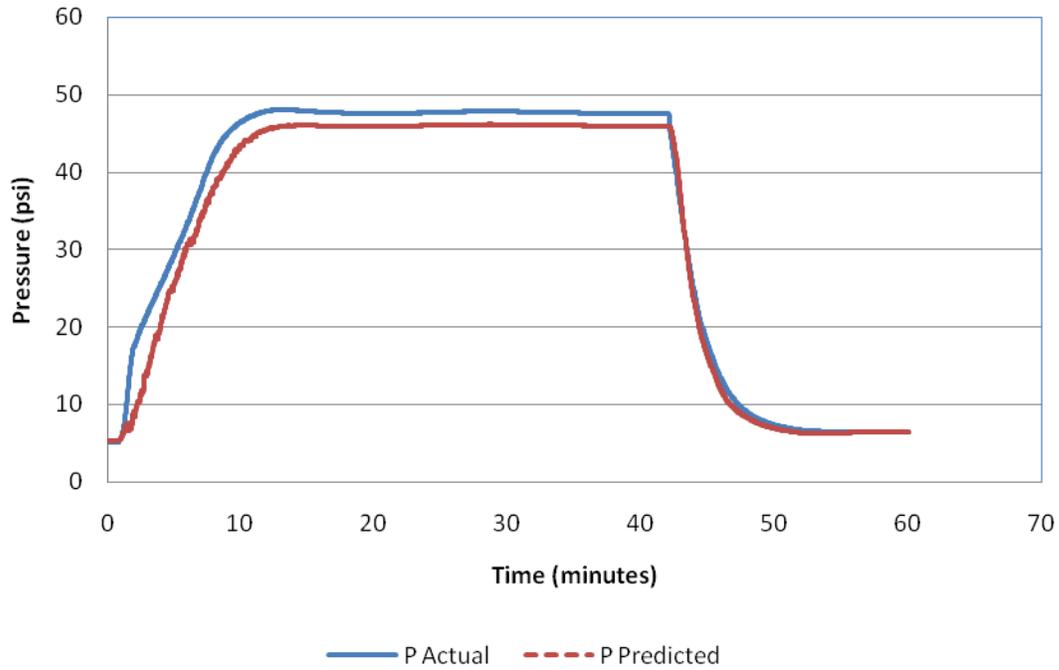


Figure 1-1. Comparison of measured and predicted internal pressure profiles for distilled water by Ghai et al. (2011)

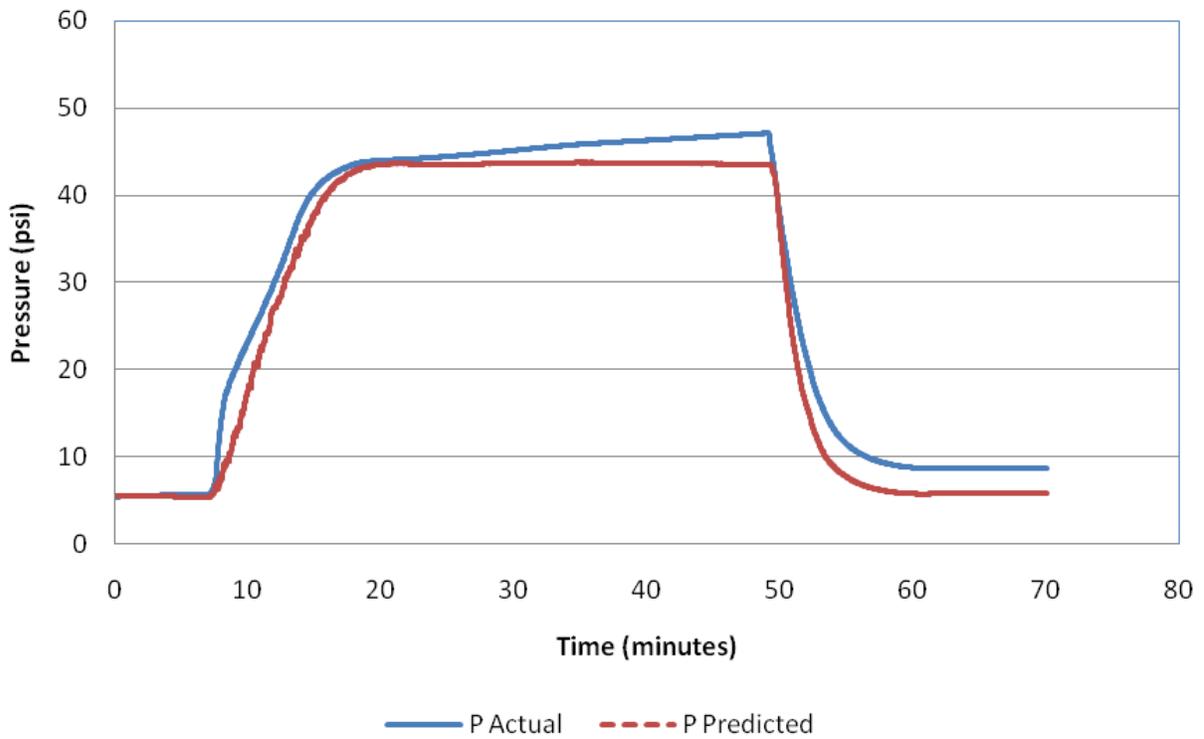


Figure 1-2. Comparison of measured and predicted internal pressure profiles for saline solution (5%) by Ghai et al. (2011)

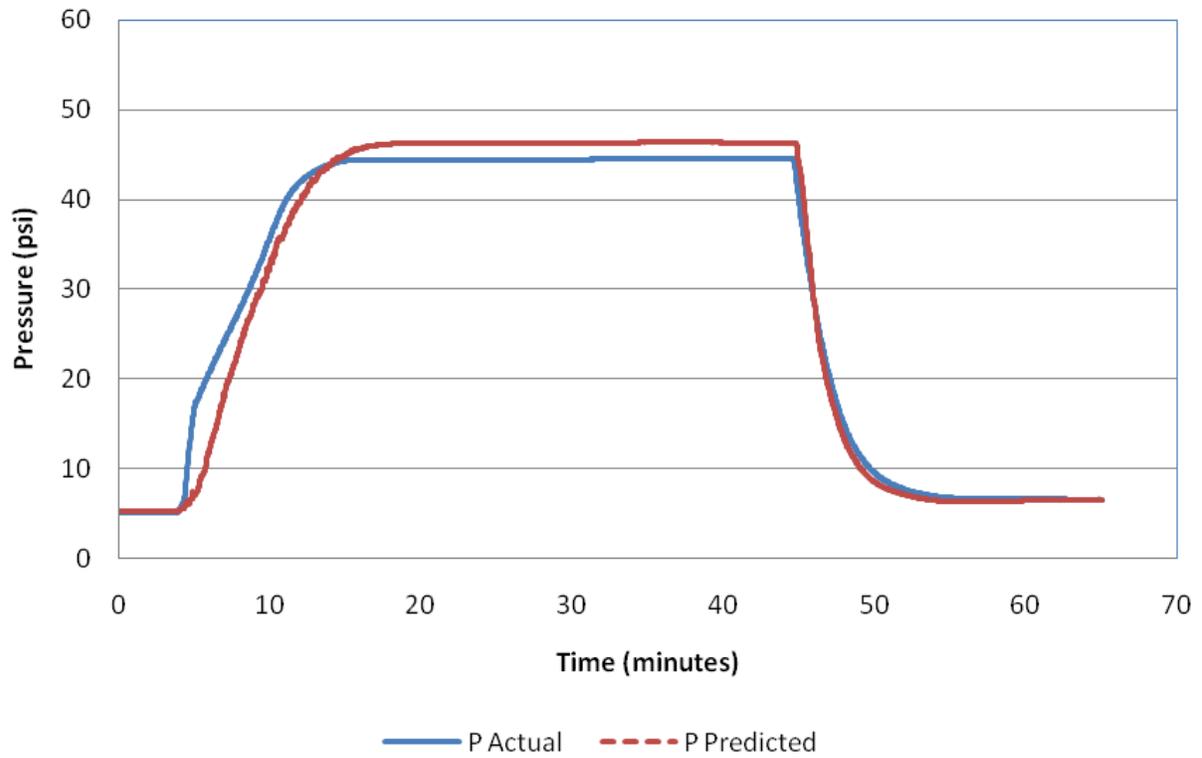


Figure 1-3. Comparison of measured and predicted internal pressure profiles for sucrose solution (10%) by Ghai et al. (2011)

## CHAPTER 2 METHODS AND PROCEDURES

To meet the above objectives, a scope of work was undertaken which consisted of the following four tasks:

### **Task 1**

The first task was to design, fabricate and test a rigid pressure-tight module for measuring and recording internal temperature data during thermal processing.

#### **Design of Module**

A pressure-tight cylindrical module was fabricated in the Agricultural and Biological Engineering Department machine shop at the University of Florida. The engineering design of the module was undertaken with the assistance of an undergraduate engineering student as a senior design project. The material of construction was chosen to be stainless steel (food grade) to avoid chemical reactions with the contents at elevated temperatures, and to comply with United States Department of Agriculture's (USDA) sanitary food processing standards and with those of the European Hygiene Engineering and Design Group (EHEDG). The module was developed to be pressure-tight and had a standard factor of safety of 3 or greater. This ensured that the module would have to be pressurized greater than 3 times its nominal operating value in order for it to fail.

#### **Fabrication and Instrumentation of Module**

The module (figure 2-1) consisted of two separate pieces, one cylindrical body and a separate circular lid piece. The capacity of the module was 430 ml. The cylindrical body had an inner diameter of 7.1 cm, a height of 10.9 cm and a wall thickness of 0.4 cm. It also contained two holes in the side wall, one near the top and the other near the

bottom to accommodate thermocouples. Two female-ends of K-type thermocouples were inserted horizontally through the holes in the body of the module to reach the center line and permanently sealed. One of these was 0.6 cm from the top of the body and the other was 1.0 cm from the bottom, leaving the two thermocouples 8.6 cm apart. The bottom cylinder also had a flange with an outer diameter of 10.0 cm and a wall thickness of 0.4 cm, to accommodate bolts on the lid for a pressure-tight seal.

The lid was fabricated to fit over the body with an O-ring gasket. It had six holes drilled symmetrically along the outer diameter. Six bolts secured the lid to the body in a pressure-tight manner. The lid also had two holes in the center to accommodate a dial gauge to measure internal pressure and an inlet valve through which to draw vacuum. An Ashcroft® pressure gauge was installed to easily check for the pressure-tight nature of the lid. The vacuum inlet had a stainless steel ball valve leading to a temporary connection with a tube to pull vacuum into the module.

### **Testing the Module**

The module was first tested on the bench-top to ensure proper functionality and no leakage. It was filled with distilled water, sealed under vacuum and kept on the bench for over two hours to check for a constant pressure reading and no loss in vacuum. It was necessary to check that the module was pressure-tight and indicated a constant value of pressure without slowly increasing to atmospheric pressure. Upon confirmation of its leak-proof nature, the module was declared fit for experimental runs.

### **Task 2**

The second task was to measure and record internal temperatures during triplicate pilot plant retort runs for each of the three aqueous solutions, pure distilled water or saline solution (5%) or sugar solution (10%), for each set of experiments.

## **Experimental Set-up**

The experimental set-up consisted of the module, vacuum pump and steam retort figure 2-2).

**Module.** A constant headspace of 8mm was marked on the inside wall of the module and the aqueous solution was filled up to this point for each run. The volume of solution in each run was 410ml. Prior to each experimental run, the solution was weighed and measured for exact volume. The lid was bolted on to the module with the six bolts.

**Vacuum pump.** The ball valve for drawing vacuum was opened and vacuum was drawn with a 1/3 horse power Emerson® vacuum pump to 15 inches Hg (~0.5 atm or 50.8 kPa). The valve was closed when desired vacuum level was reached.

**Steam retort.** The module was placed inside a pilot scale still cook steam retort (figure 2-3) in the Food Science and Human Nutrition Department Pilot Plant, at University of Florida. The retort was equipped with a pressure-tight packing gland on the side wall to accommodate lead cables for thermocouples to pass through the retort. It was also equipped with a Mercury in Glass (MIG) thermometer and a pressure gauge to enable external monitoring of temperatures and pressures as per FDA regulations. There was a drain at the bottom right corner for draining condensate during come-up and water during cooling period. The lid of the retort was secured by bolting down six fastening lugs in diagonally opposite pairs. A bleeder on the top of the lid was kept open throughout the operation to ensure a constant flow of steam as per safe operational procedures of thermal processing given by FDA. The retort contained an inlet for cooling water which was sprayed inside the retort through a sparger under the lid, as well as an inlet for compressed air. The steam inlet was at the bottom of the retort

through spreaders, and the steam flow control valve was automatically controlled by a pneumatic temperature recorder/controller mounted on the wall behind the retort. The process temperature chosen for retort operation was set on the recorder. The recorder controlled the amount of steam under pressure and automatically kept the retort at the constant set temperature till the set-point was manually changed.

### **Measuring and Recording Data**

A total of three lead cables passed through the packing gland on the retort, two for thermocouples inside the can and one for the thermocouple in the retort. Inside the retort, the male ends of two thermocouples were inserted into the female ends fitted on the module and one thermocouple was hung on a fixture inside the retort to measure and record retort temperatures. Outside the retort, the thermocouple lead wires were connected to an Omega® 56 data acquisition system (DAQ) (figure 2-4) which in turn was connected to a computer containing the necessary software to capture and record temperature data in real-time.

### **Experimental Procedure**

#### **Retort operation**

After placing the filled and sealed module inside the retort, all thermocouple lead wires were connected to their respective ports on the DAQ Omega® 56 before closing the retort. The thermal processing test was run for 10 minutes at 121 C (250 F). After which, steam was shut off and cooling cycle was begun.

#### **Data acquisition**

Once the retort was ready for processing, the Omega® 56 DAQ was initialized to acquire temperature data in real time. A graph of temperature versus time opened and real-time reading of temperatures were observed during the process to ensure that

desired process conditions were being achieved. At the end of cooling, the DAQ was stopped and data files were saved with appropriate batch numbers indicating the type of product and the date of the run.

### **Thermocouple calibration**

Prior to executing the experiments, it was necessary to calibrate all thermocouples. To do this, an experiment was run with all connections described above. But, the module was placed in the retort, open and empty, to record the saturated steam conditions in the retort. The three thermocouples, two inside the module and one hung on the interior wall of the retort were exposed to the steam in the retort. The experiment was run with steam, and data were collected to note temperature readings for all thermocouples during the come-up, holding and cooling periods. The readings and errors (if any) were recorded to calibrate the thermocouples in order to record the same temperatures at the same time intervals. (figure 2-5)

### **Design and Execution of Experiments**

Three experimental replicate runs on each aqueous solution food system were carried out, with initial conditions (table 2-1) for each system as follows:

#### **Distilled water**

Distilled water was used first, being the simplest food system, and as the baseline for experimental runs. In a clean beaker, about 500ml distilled water was brought to boil to evaporate dissolved gases. The water was allowed to cool down and 410ml was collected in a beaker. Exact volume, weight and initial temperature of the water were measured and recorded before being added to the module.

### **Saline solution (5%)**

Table salt (food grade) from a local supermarket was used for making the saline solution. Considering a pre-decided volume of solution as 410ml, calculations were made to determine the amount of salt to be dissolved to keep the initial concentration as 5% salt solution. Excess amount of distilled water was boiled to evaporate dissolved gases and cooled. The required amount was poured into a beaker and the calculated amount of salt was added to it and dissolved. Exact volume, weight and initial temperature of the solution were measured and recorded before being added to the module.

### **Sucrose solution (10%)**

Powdered sugar (food grade) from a local supermarket was used for making the sucrose solution (10%) in a similar manner as described above for saline solution.

### **Task 3**

The third task was to predict internal pressure profiles in response to the recorded temperature profiles using the mathematical model developed by Ghai et al. (2011) for each of the three above aqueous solutions. This model was designed to predict the internal headspace pressure  $P_t(T)$  as a sum of the pressures exerted by the vapor  $P_w(T)$  and the gaseous  $P_2(T)$  phases:

$$P_t(T) = P_w(T) + P_2(T)$$

The model is described below:

### **Model for Distilled Water**

The internal pressure of plain distilled water was the sum of the pressure exerted by water vapor and the pressure exerted by the gas phase.

The vapor pressure of pure water was a function of real-time temperature and was calculated using the expression taken from the International Association for the Properties of Water and Steam (IAPWS) adopted in 1995:

$$\text{Log}_e (P_w / 22.064 \cdot 10^6) = 647.096/T * (- 7.85951783 \cdot v + 1.84408259 \cdot v^{1.5} - 11.7866497 \cdot v^3 + 22.6807411 \cdot v^{3.5} - 15.9618719 \cdot v^4 + 1.80122502 \cdot v^{7.5})$$

with temperature (T) in Kelvin and pressure ( $P_w$ ) in Pascals and,

$v = 1 - T/647.096$ , where the value 647.096 K is the triple point of water.

The pressure exerted by the gaseous phase for a reversible adiabatic (Isentropic) process with a specific heat ratio of 1.35 as a function of the initial pressure, and the initial and final temperatures is:

$$P_2 = P_1 * (T_2 / T_1)^{3.86}$$

Thus, the total predicted pressure profile of pure distilled water was the addition of the pressures exerted by the vapor and the gaseous phases:

$$P_t(T) = P_w(T) + P_2(T)$$

### **Model for Saline Solution (5%)**

The mathematical model for predicting the internal pressure of saline solution was the sum of pressure exerted by the vapors of the solution, as a function of real-time temperature; and pressure exerted by the gas phase as a function of initial and final (real-time) temperatures.

The pressure exerted by water vapors from the solution as a function of temperature was calculated by applying Raoult's Law to the IAPWS formulation. Raoult's Law states that the vapor pressure of a solution of a non-volatile solute is equal to the vapor pressure of the pure solvent at that temperature multiplied by its mole fraction. In equation form, this reads:

$$P = x_{\text{solv}} * P^{\circ}_{\text{solv}}$$

where  $P^{\circ}_{\text{solv}}$  is the vapor pressure of the pure solvent at a particular temperature, and  $x_{\text{solv}}$  is the mole fraction of the pure solvent in the solution.

The mole fraction of water was calculated in the saline solution and was multiplied by the vapor pressure data of pure water calculated at a particular temperature using the IAPWS formulation to get the final vapor pressure.

Since, the presence of a non-volatile solute had no effect on the pressure exerted by the gaseous phase; it was calculated in a way similar to distilled water.

Pressures exerted by the vapor and the gaseous phases were then added to get the final predicted internal pressure profile of the saline solution (5%) as a model food system.

$$P_t(T) = P_w(T) + P(T)$$

### **Model for Sucrose Solution (10%)**

The total internal pressure of the sucrose solution, as a food product system, was calculated using a method similar to that of saline solution, but changing the mole fraction of the non-volatile solute in the solution.

$$P_t(T) = P_w(T) + P(T)$$

With the model, headspace pressure profiles were predicted in response to internal temperature profiles. Two pressure profiles were obtained for each food system, one calculated with temperature profile of the thermocouple at the top of the module and one at the bottom. Plots were made for theoretical pressure profiles, two plots for each food system for comparison studies in the next task.

#### **Task 4**

The final task was to compare predicted profiles of headspace pressure obtained in response to temperatures at the top with those from the bottom of the module, while it was being thermally processed. The two pressure profiles obtained were plotted on the same graph to observe the difference in values of predicted pressures at any given time during come-up time, for each solution. Particular attention was given to observing the pressure differences during initial come-up time and comparing them with the differences reported by Ghai et al. (2011) during the same process. This task was carried out by following these three steps:

1. Predicted pressure profiles were plotted in response to top and bottom temperatures. The pressure differences were determined at points in time during the come-up period.
2. The data obtained by Ghai et al. (2011) were plotted to show the differences between predicted and experimentally measured pressures they obtained.
3. The above two sets of pressure profiles differences were compared to determine if these differences followed a similar pattern, and could offer explanation for differences between measured and predicted pressures in the previous work by Ghai et al. (2011).

Table 2-1. Initial product and process conditions for retort experiments with rigid pressure tight module

Product	Volume (milliliters)	Weight (grams)	Headspace (millimeters)	Vacuum drawn in the headspace (kiloPascals)	Initial Temperature (degree Celsius)
Distilled Water	410	410	8	50.8	28
Saline solution (5%)	410	410	8	50.8	25
Sucrose solution (10%)	410	410	8	50.8	25



Figure 2-1. Stainless steel module used to record temperatures during thermal processing in the retort

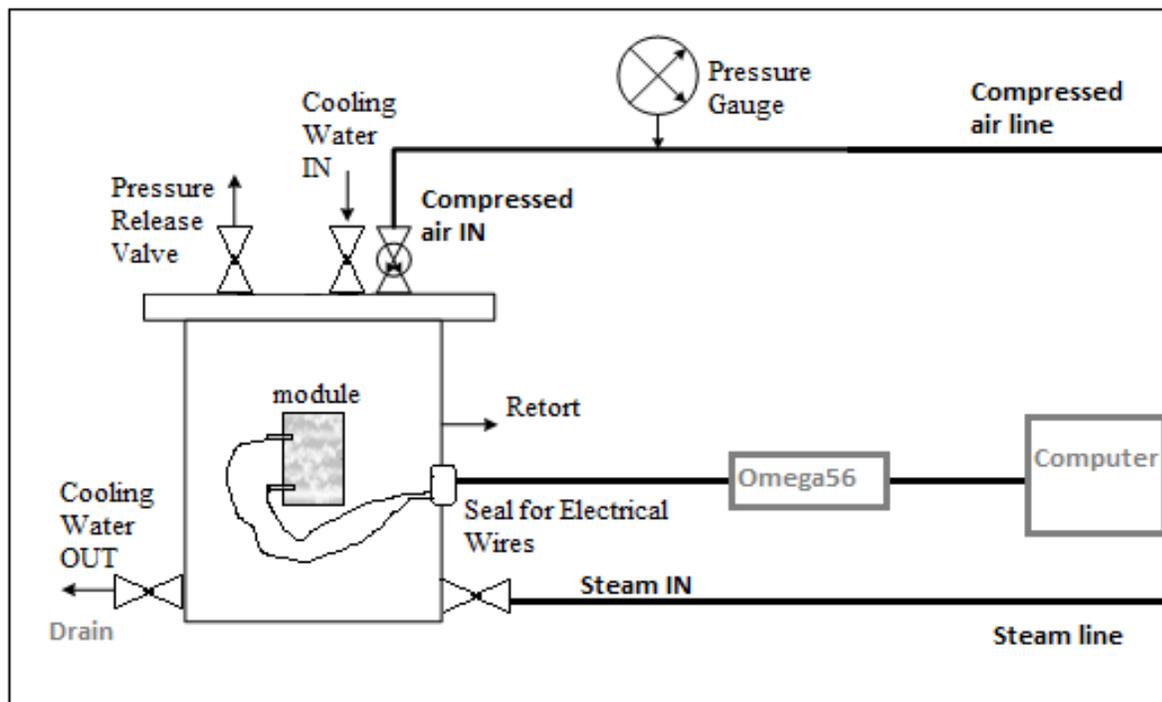


Figure 2-2. Experimental set-up for the thermal processing runs



Figure 2-3. Still steam retort at the Food Science and Human Nutrition pilot plant, University of Florida



Figure 2-4. Omega® 56 data acquisition system used to measure temperatures inside the module

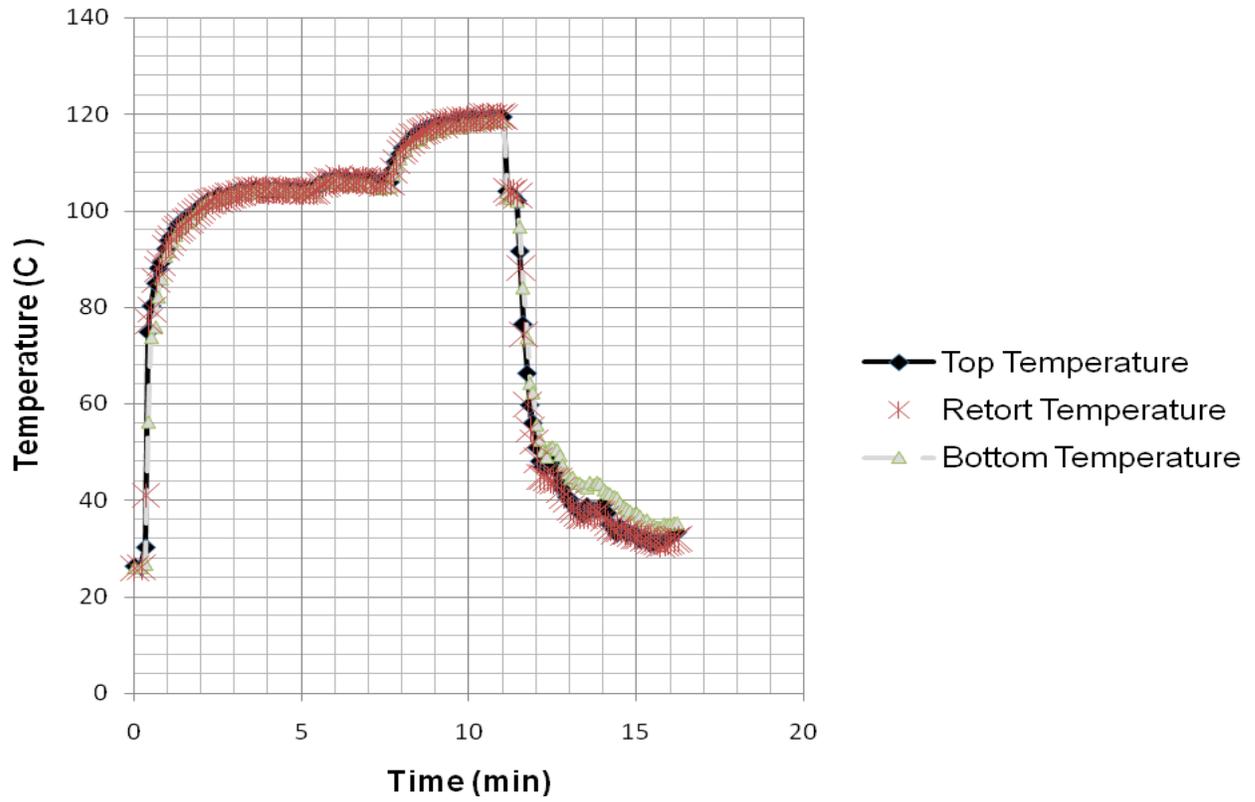


Figure 2-5. Calibration of thermocouples used to measure temperatures during thermal processing runs

## CHAPTER 3 RESULTS

### **Distilled Water**

Profiles of experimentally measured temperatures versus time were plotted in figure 3-1. Starting at an initial temperature of about 28 C in the solution, both temperatures increased steadily in the first eight minutes of the process, signifying the come-up period, leveling out at a constant temperature at ten minutes. After they leveled, the retort was kept at this constant temperature for ten more minutes, called the holding period. When the holding period ended, the steam was shut off and cooling water was introduced to commence the cooling period. During the first ten minutes of the process, the come-up period, both temperatures followed different trajectories, the temperature at the top consistently higher than the temperature at the bottom. The temperature at the top (black line) showed a steep increase from 29 C to 87 C after two minutes whereas the bottom temperature (grey line) only increased to 55 C during the same time interval. Note that four minutes into the process, top temperature had rocketed to 118 C, but, the bottom temperature was slower to rise reaching a value of only 103 C at four minutes. Finally, at ten minutes, temperatures at the top and bottom leveled off and stayed constant throughout the holding period. The following discussion focuses strictly on the first ten minutes (come-up time).

Figure 3-2 shows both top and bottom temperatures and predicted pressure profiles in response to those top and bottom temperature profiles versus time, for the system of pure distilled water. Predicted pressures in kiloPascals were plotted on the primary vertical axis along with temperatures at the top and bottom from figure 3-1 on the secondary vertical axis. The module was filled, sealed and a vacuum of 15 inch Hg

was drawn, which corresponded to 0.5 atm or 7.3 psi or 50.8 kPa. For convenience, pressures predicted from top and bottom temperatures are denoted by pressure from top temperature (black line) and pressure from bottom temperature (grey line), respectively. At four minutes, the temperature at the top was about 118 C and the corresponding predicted pressure was 326 kPa. Simultaneously, the bottom temperature, lesser than the top, was 103 C which produced a predicted pressure value of only 232 kPa. The difference between predicted pressures at a time instant of four minutes was 94 kPa when the difference in top and bottom temperatures was about 15 C. As compared to pressure from top temperature, the pressure from bottom temperature took longer to achieve constant values since the bottom temperature rose slower than the top. This variation in increasing pattern of predicted pressures from top and bottom temperatures was due to the different temperature curves measured at the top and bottom of the module, as observed in figure 3-1.

Figure 3-3 shows predicted and experimentally measured pressure profiles for distilled water by Ghai et al. (2011). Pressures were predicted by applying the mathematical model developed by Ghai et al. (2011) to their experimentally measured temperatures measured at the bottom of the module. The module they used was sealed at about 34.5 kPa of vacuum (lower than the 50.8 kPa used in present work). After the first minute, both measured pressure (black line) and predicted pressure (grey line), exhibited different curves, the former sharper than the latter. Measured pressure rocketed to 174 kPa at four minutes. Simultaneously, predicted pressure ascended to only 147 kPa. The significant difference in predicted and measured pressure profiles

during the come-up time in the work by Ghai et al. (2011) presented an opportunity of improvement in the current experimental work.

Predicted pressure profiles from top and bottom temperatures by Paluri and predicted and measured pressure profiles by Ghai et al. (2011) are shown in figure 3-4. Differences between the values of predicted pressures from top and bottom temperatures by Paluri, and differences between measured and predicted pressures by Ghai et al. (2011) were denoted as Delta Paluri and Delta Ghai, respectively. The differences, Delta Paluri and Delta Ghai, were of the same order of magnitude. For example, at four minutes, Delta Paluri was 94 kPa and Delta Ghai was 27 kPa. Figure 3-5 shows the pattern of these pressure differences, Delta Paluri and Delta Ghai, over time. The delta pressure profiles, Delta Paluri and Delta Ghai, showed a similar trend in their patterns. Differences in their actual values were attributed to the fact that retort operating and process conditions used by Ghai et al. (2011) differed from those used in this study.

### **Saline Solution (5%)**

Similar to the case of distilled water, five figures were plotted for data analysis. Profiles of experimentally measured temperatures versus time were plotted in figure 3-6. The following discussion focuses strictly on the first ten minutes (come-up time). Figure 3-7 shows both top and bottom temperatures and predicted pressure profiles in response to those top and bottom temperature profiles versus time, for the system of saline solution (5%). At four minutes, the temperature at the top was about 106 C and the corresponding predicted pressure was 250 kPa. Simultaneously, the bottom temperature, lesser than the top, was 91 C which produced a predicted pressure value of only 181 kPa. The difference between predicted pressures at a time instant of four

minutes was 68 kPa when the difference in top and bottom temperatures was about 15 C. As compared to pressure from top temperature, the pressure from bottom temperature took longer to achieve constant values since the bottom temperature rose slower than the top. This variation in increasing pattern of predicted pressures from top and bottom temperatures was a due to the different temperature curves measured at the top and bottom of the module, as observed in figure 3-6. Figure 3-8 shows predicted and experimentally measured pressure profiles for distilled water by Ghai et al. (2011). Measured pressure rocketed to 173 kPa at four minutes while predicted pressure ascended to only 141 kPa. Predicted pressure profiles from top and bottom temperatures by Paluri and predicted and measured pressure profiles by Ghai et al. (2011) for saline solution (5%) are shown in figure 3-9. Differences between the values of predicted pressures from top and bottom temperatures by Paluri, and differences between measured and predicted pressures by Ghai et al. (2011) were denoted as Delta Paluri and Delta Ghai, respectively. The differences, Delta Paluri and Delta Ghai, were of the same order of magnitude. For example, at four minutes, Delta Paluri was 68 kPa and Delta Ghai was 32 kPa. Figure 3-10 shows the pattern of these pressure differences, Delta Paluri and Delta Ghai, over time. Similar to the case of distilled water, the delta pressure profiles, Delta Paluri and Delta Ghai, showed a similar trend in their patterns.

### **Sucrose Solution (10%)**

Figures 3-11, 3-12, 3-13, 3-14, 3-15 contain plots for sucrose solution (10%) corresponding to the plots for distilled water and saline solution (5%). Similar analysis was made for all three aqueous solutions.

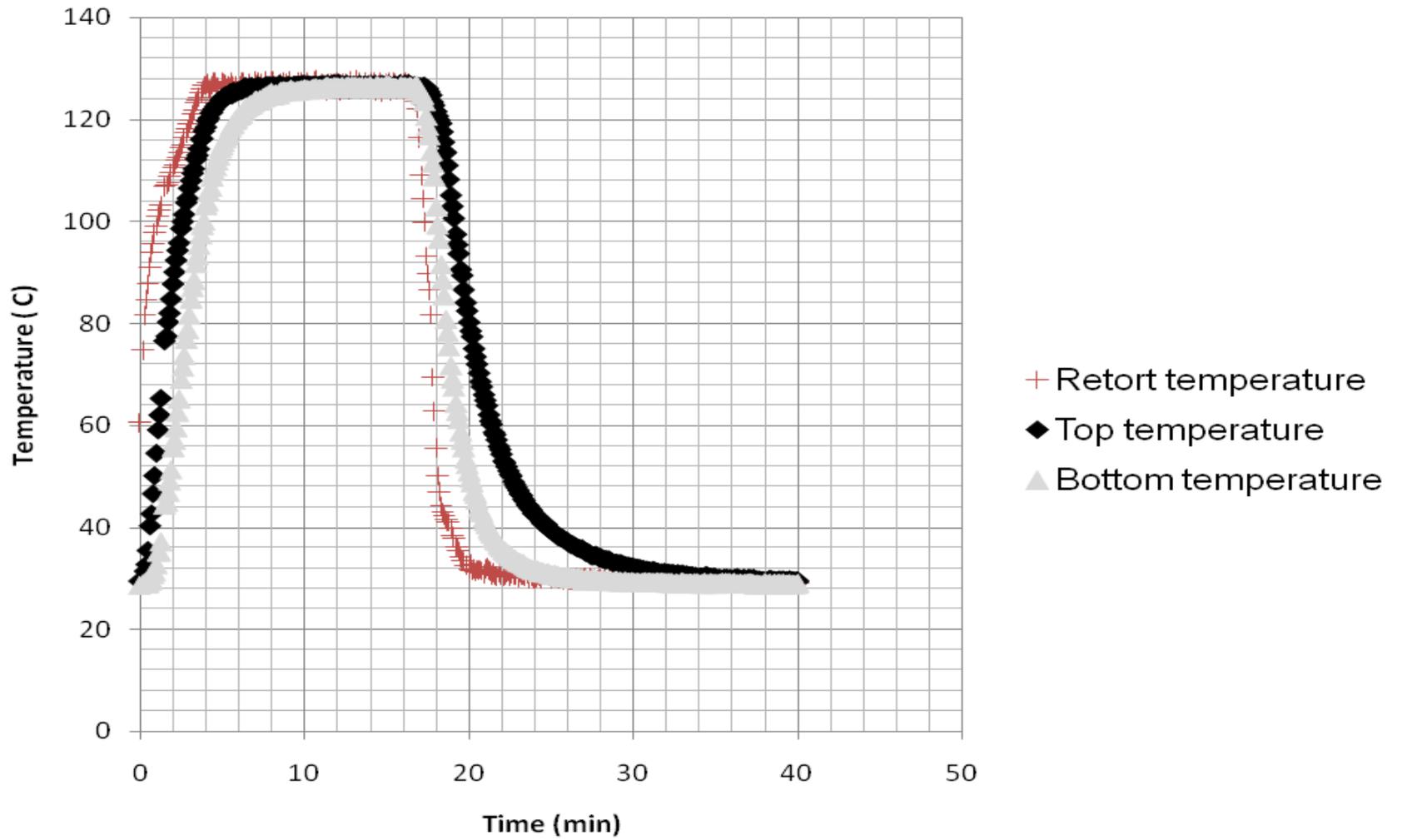


Figure 3-1. Measured temperatures versus time at top and bottom of pressure-tight module during retort process for distilled water by Paluri

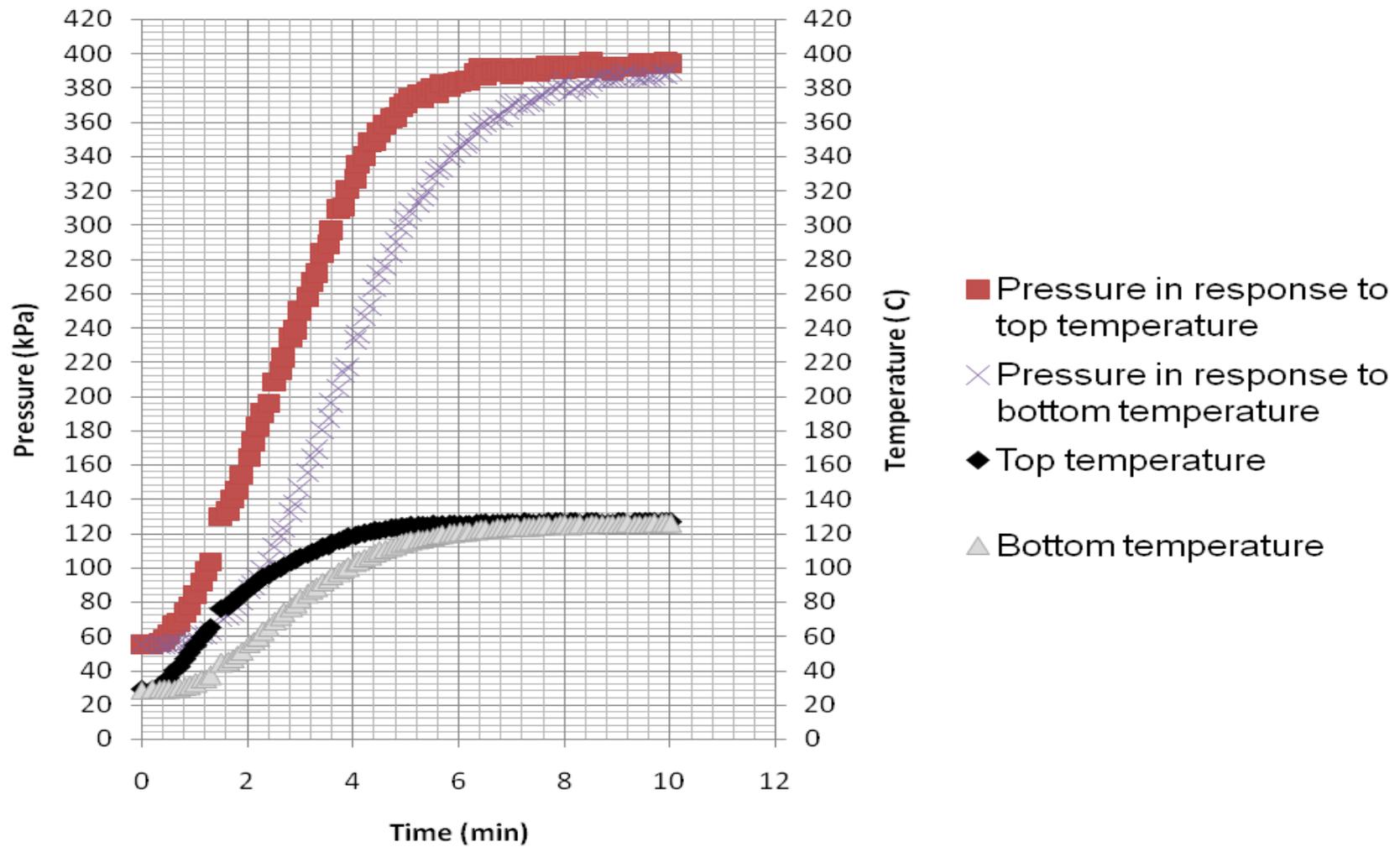


Figure 3-2. Top and bottom temperature profiles along with predicted pressure profiles in response to top and bottom temperature profiles for distilled water by Paluri

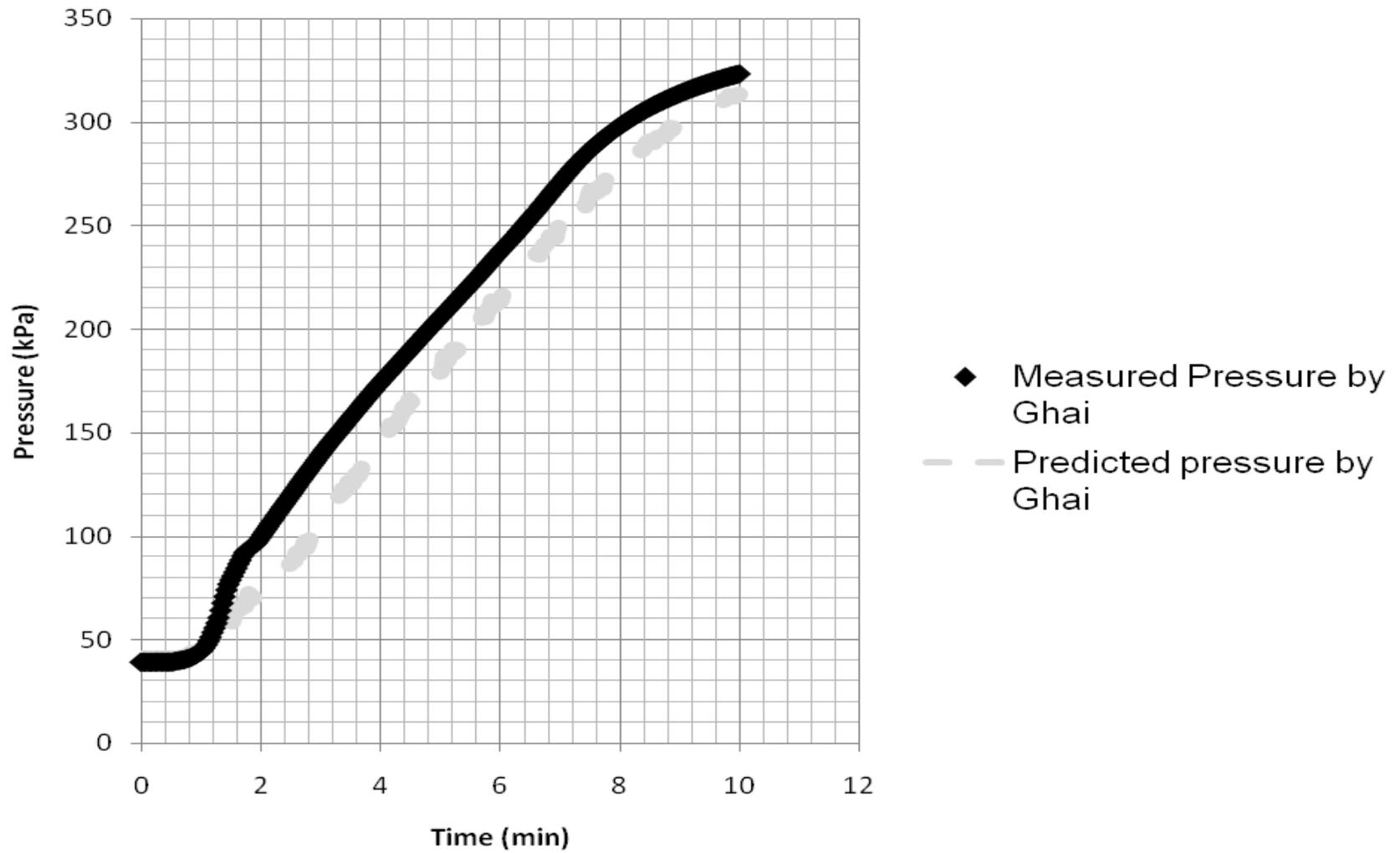


Figure 3-3. Predicted and experimentally measured pressure profiles by Ghai et al. (2011) for distilled water

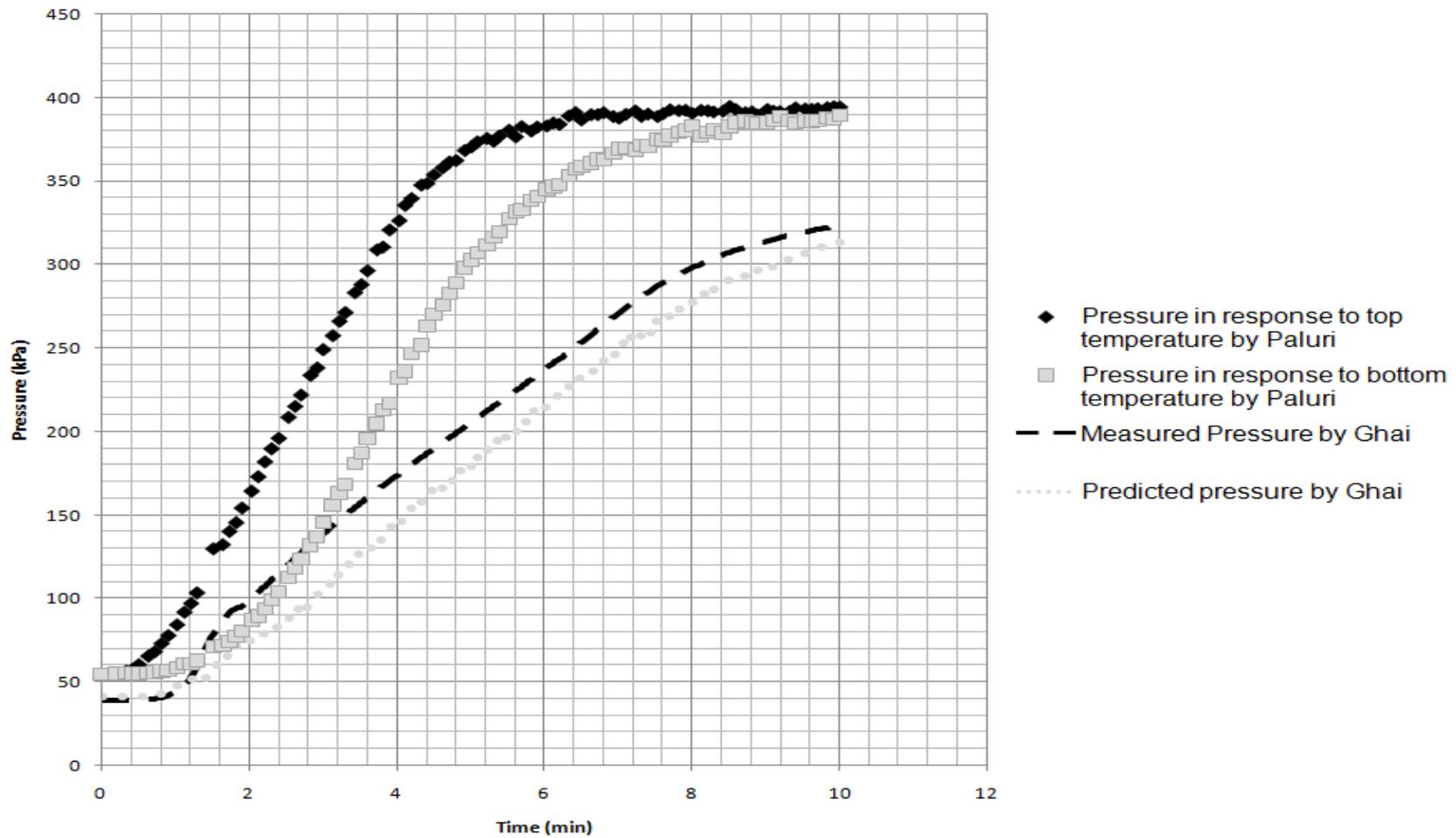


Figure 3-4. Predicted pressure profiles from top and bottom temperatures by Paluri and predicted and measured pressure profiles by Ghai et al. (2011) for distilled water

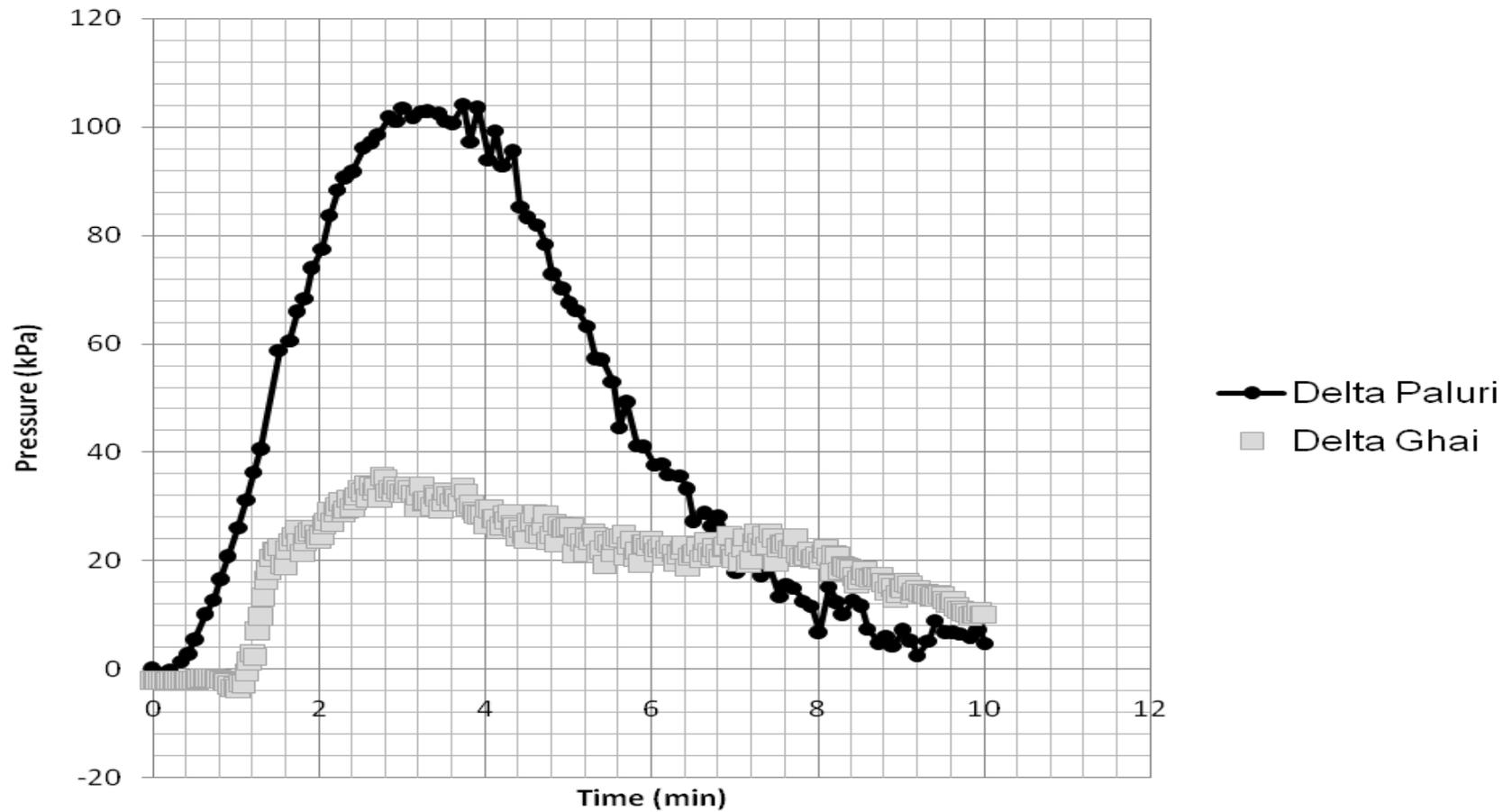


Figure 3-5. Comparison of difference in pressure profiles predicted from the top and bottom temperatures (Delta Paluri) with differences between predicted and measured profiles reported by Ghai et al. (2011) (Delta Ghai) for distilled water

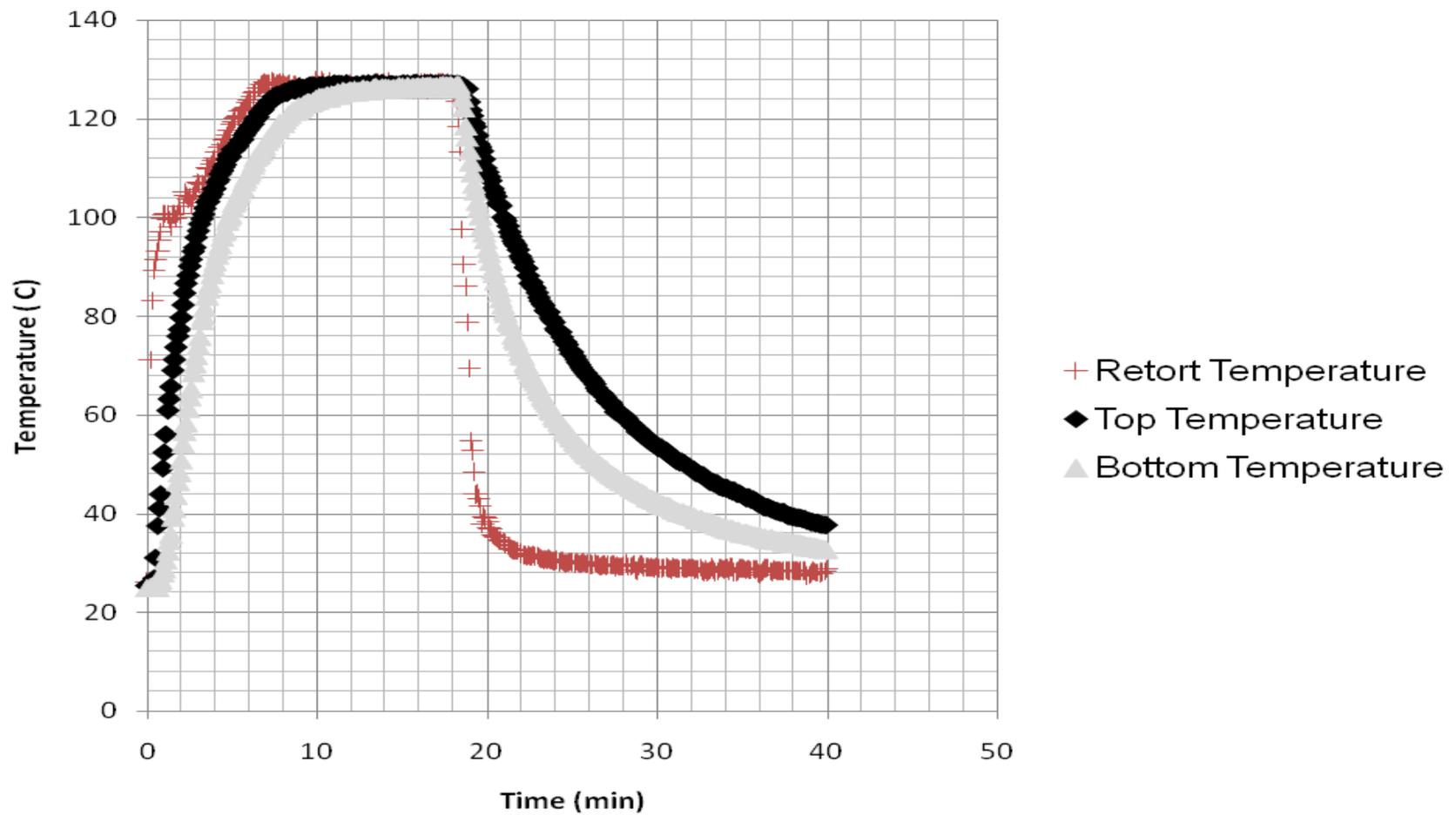


Figure 3-6. Measured temperatures versus time at top and bottom of pressure-tight module during retort process for saline solution (5%) by Paluri

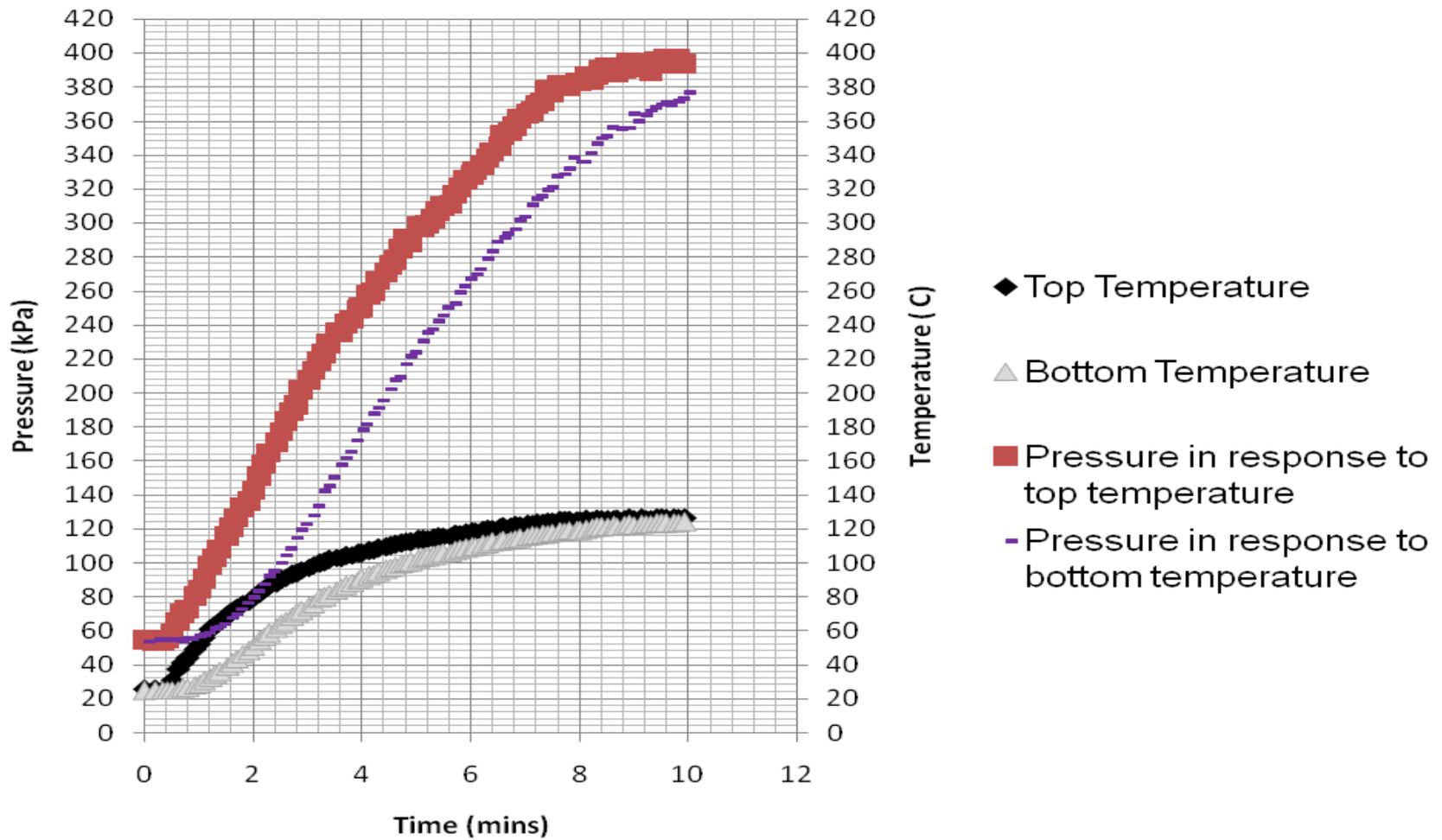


Figure 3-7. Top and bottom temperature profiles along with predicted pressure profiles in response to top and bottom temperature profiles for saline solution (5%) by Paluri

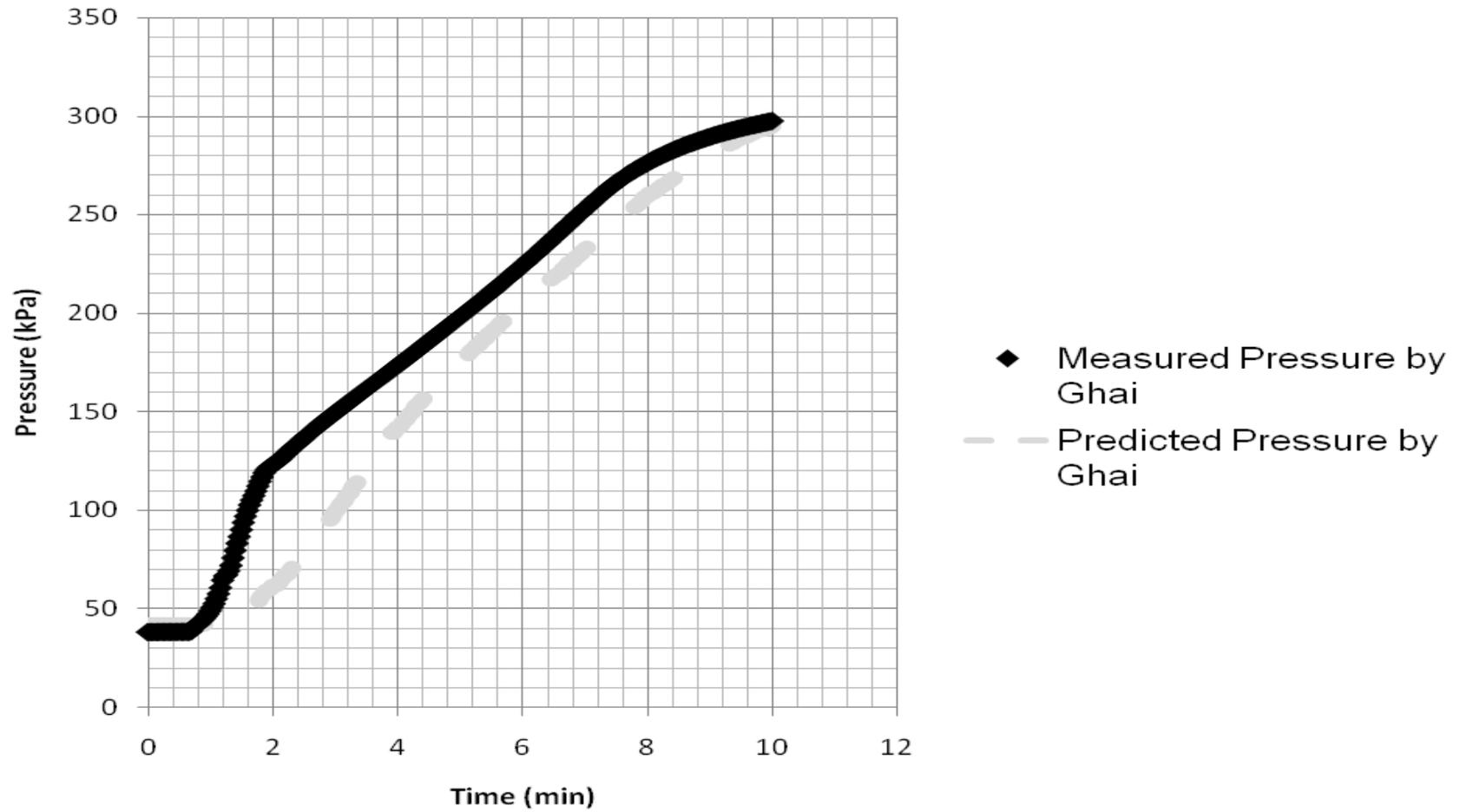


Figure 3-8. Predicted and experimentally measured pressure profiles by Ghai et al. (2011) for saline solution (5%)

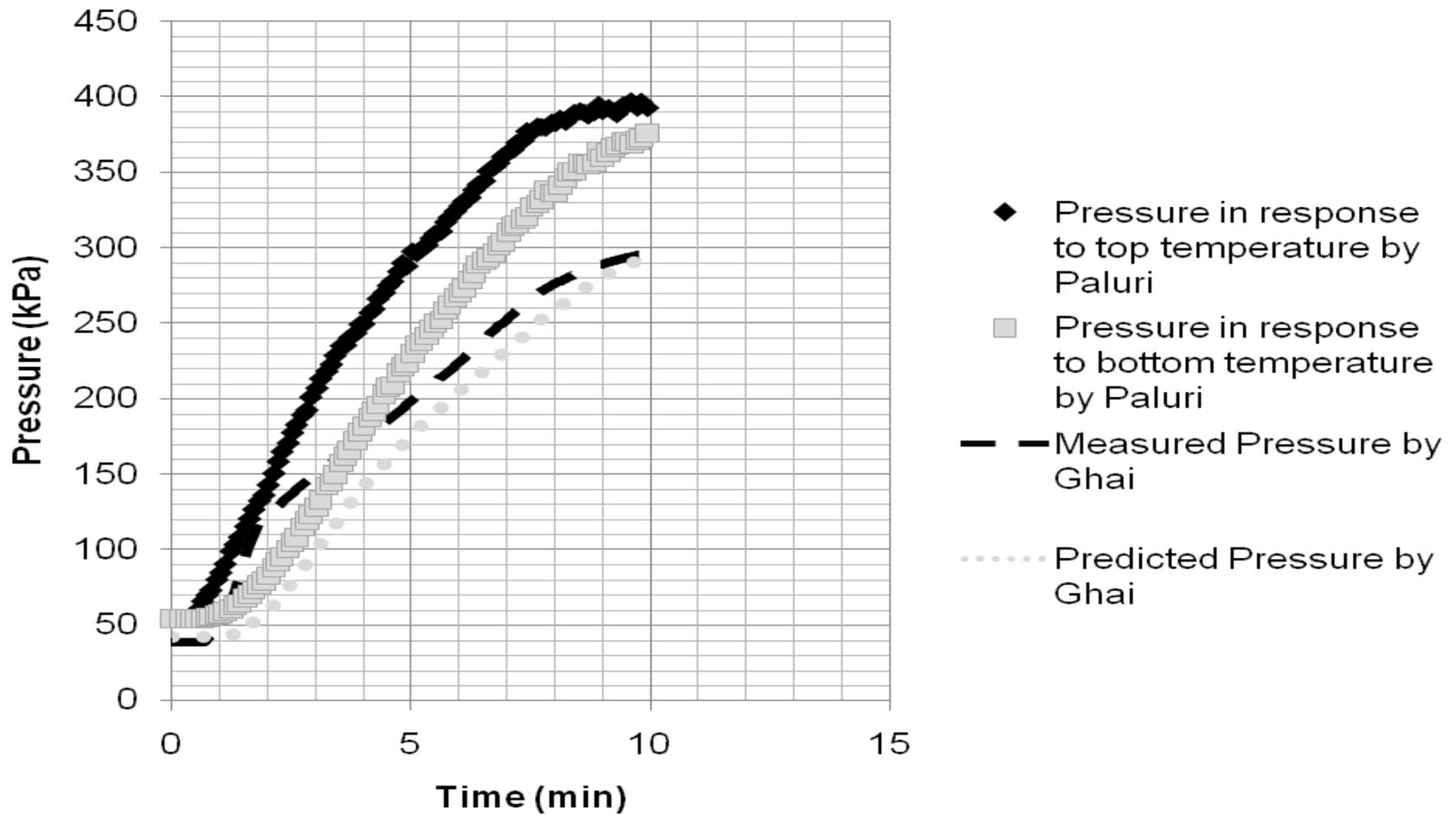


Figure 3-9. Predicted pressure profiles from top and bottom temperatures by Paluri and predicted and measured pressure profiles by Ghai et al. (2011) for saline solution (5%)



Figure 3-10. Comparison of difference in pressure profiles predicted from the top and bottom temperatures (Delta Paluri) with differences between predicted and measured profiles reported by Ghai et al. (2011) (Delta Ghai) for saline solution (5%)

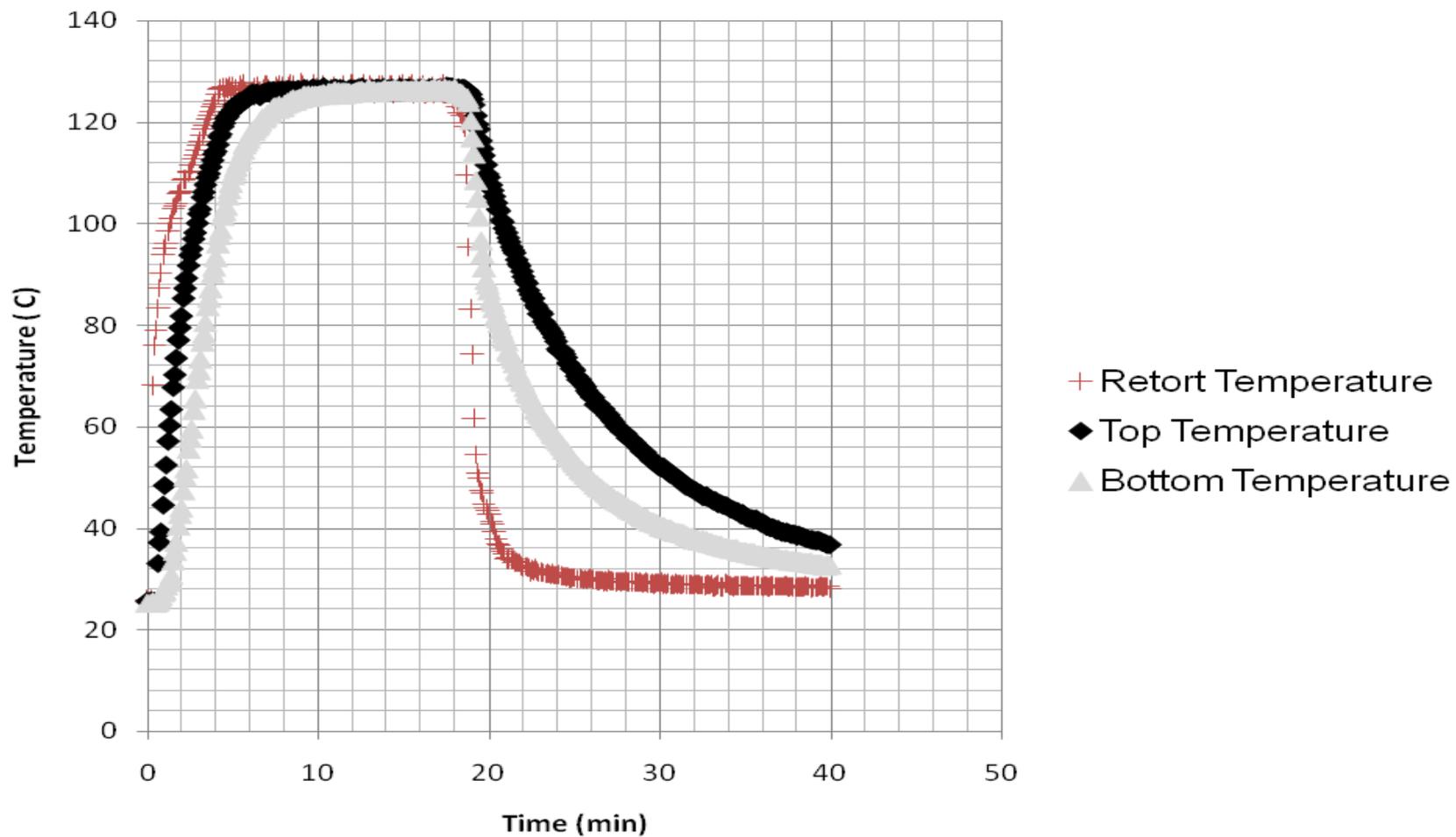


Figure 3-11. Measured temperatures versus time at top and bottom of pressure-tight module during retort process for sucrose solution (10%) by Paluri

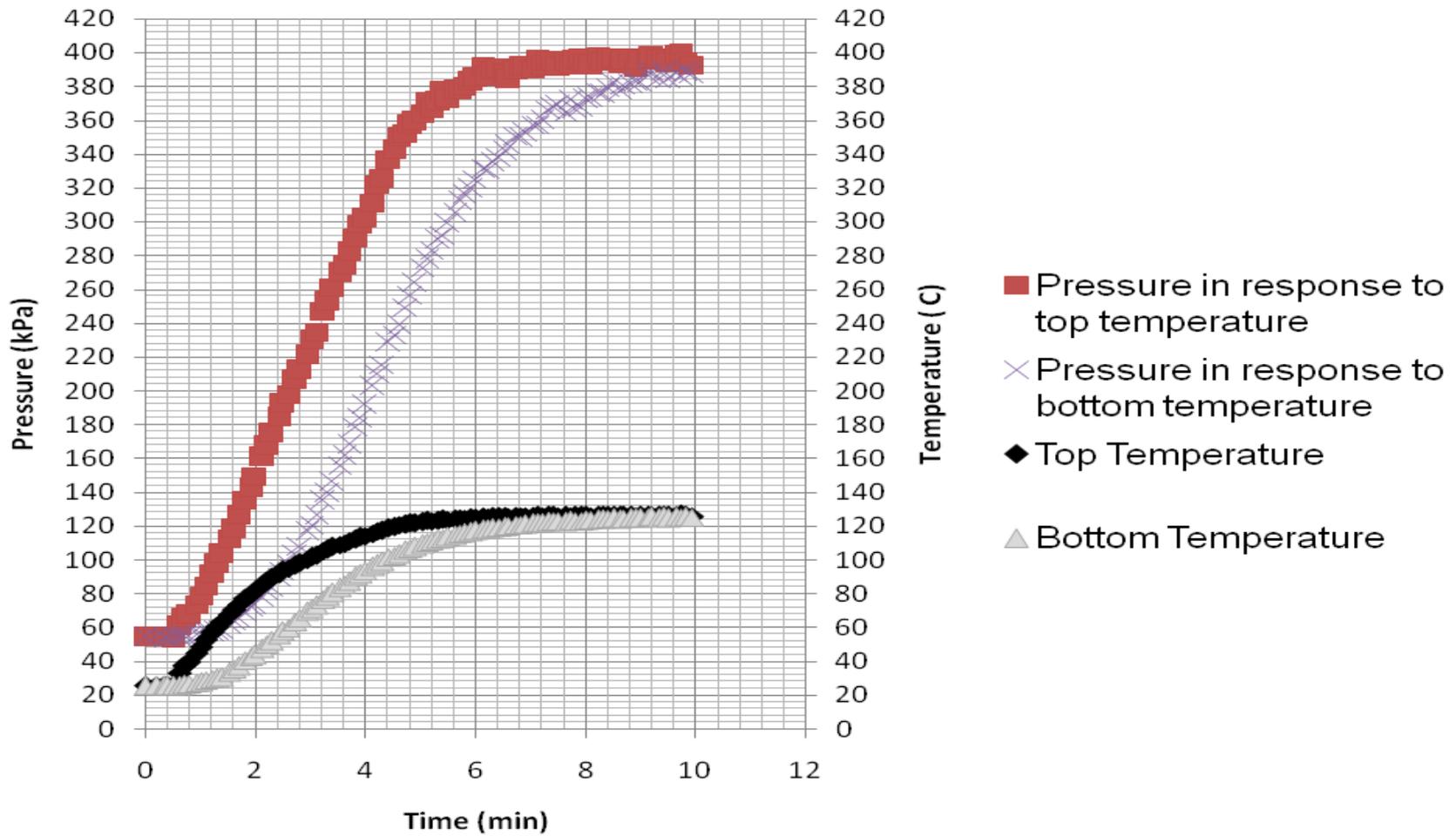


Figure 3-12. Top and bottom temperature profiles along with predicted pressure profiles in response to top and bottom temperature profiles for sucrose solution (10%) by Paluri

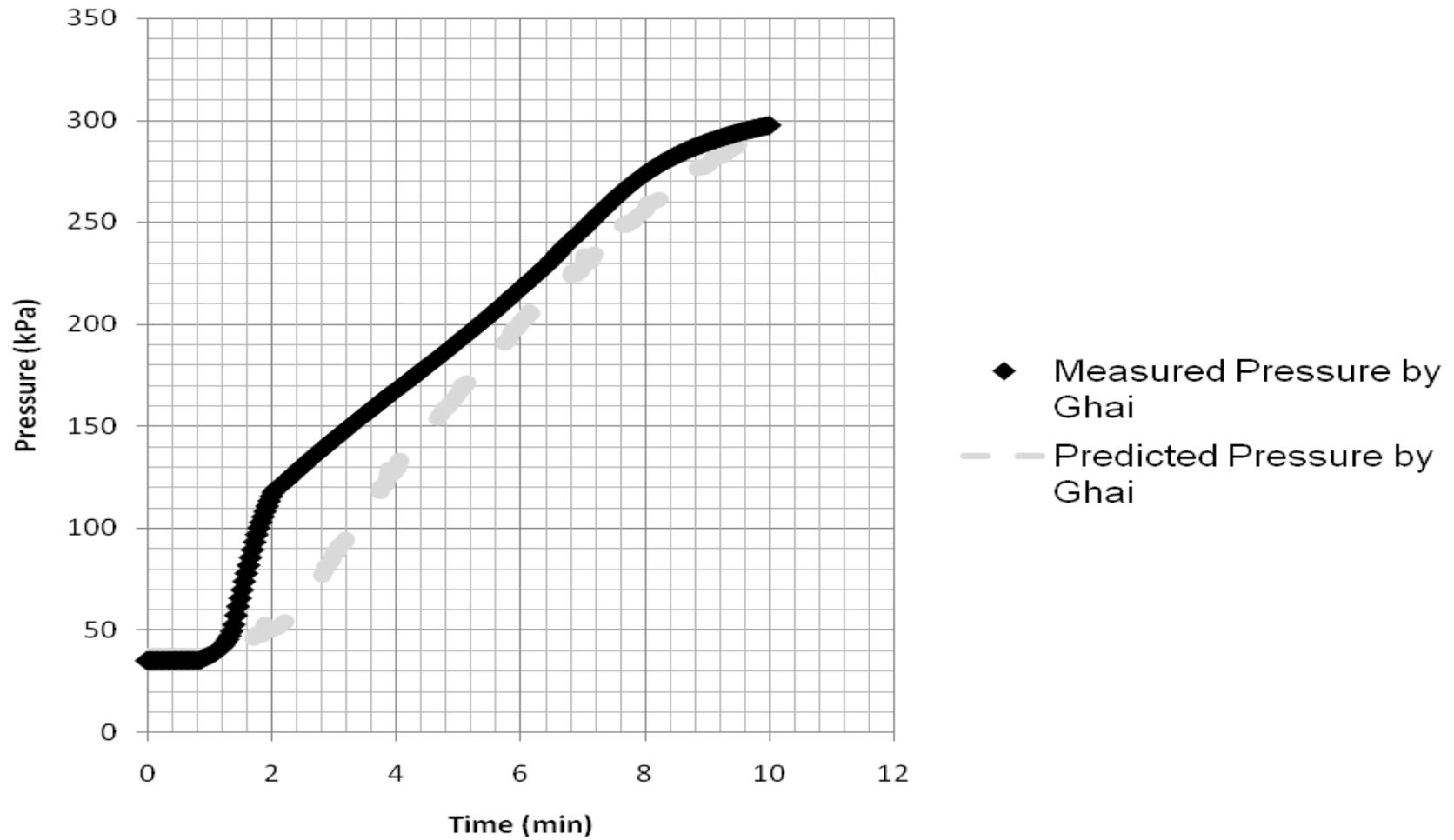


Figure 3-13. Predicted and experimentally measured pressure profiles by Ghai et al. (2011) for sucrose solution (10%)

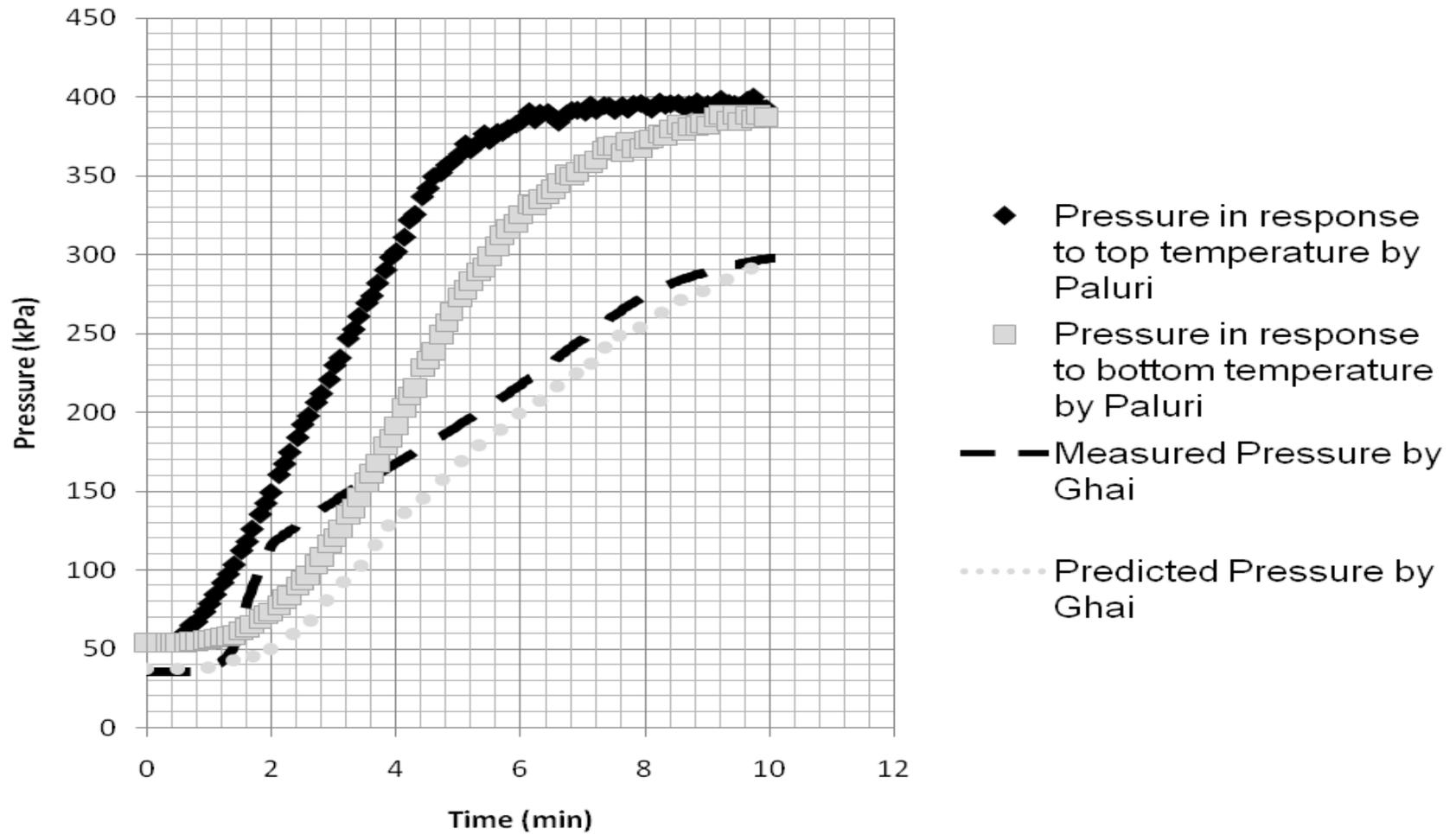


Figure 3-14. Predicted pressure profiles from top and bottom temperatures by Paluri and predicted and measured pressure profiles by Ghai et al. (2011) for sucrose solution (10%)

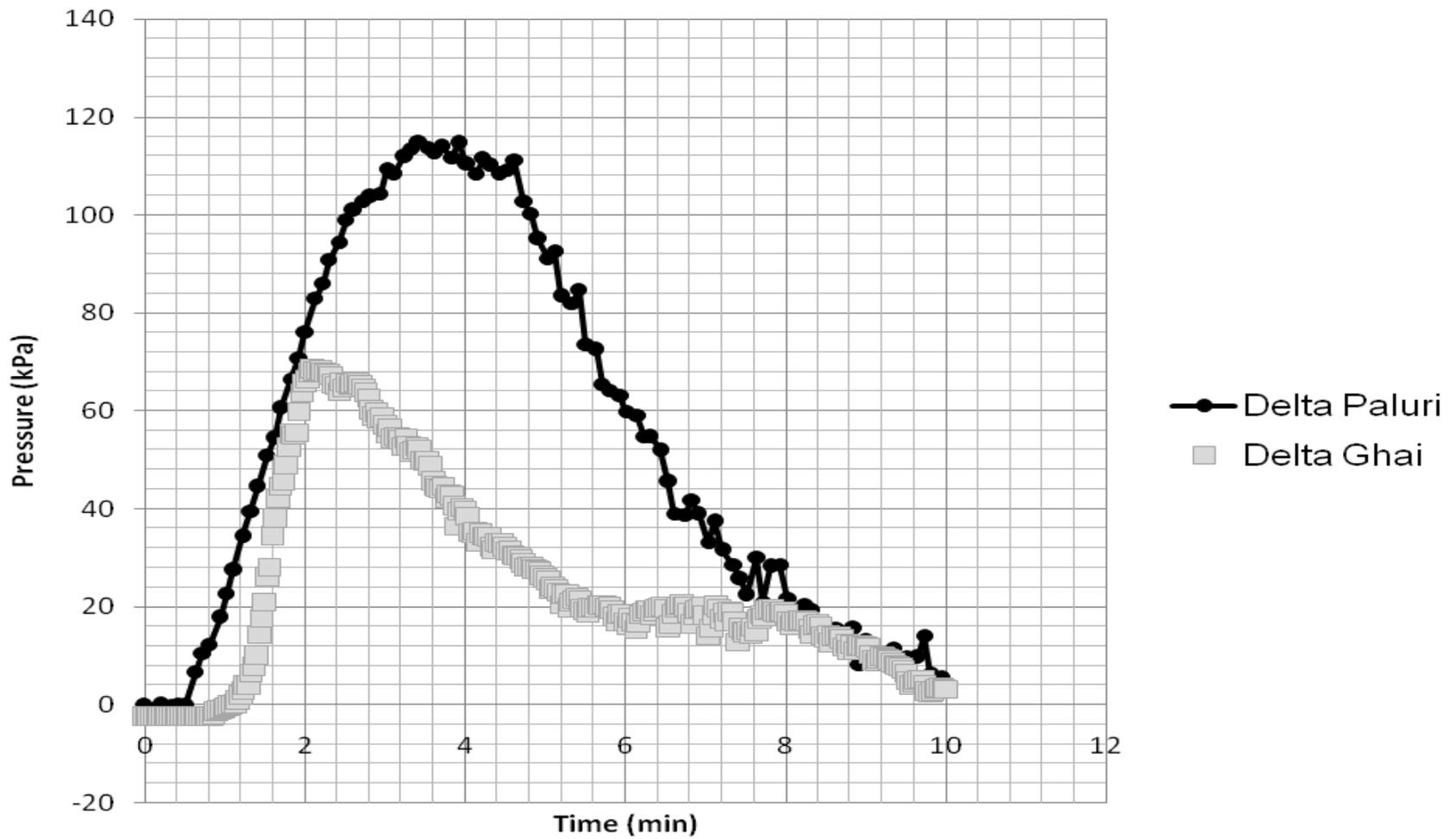


Figure 3-15. Comparison of difference in pressure profiles predicted from the top and bottom temperatures (Delta Paluri) with differences between predicted and measured profiles reported by Ghai et al. (2011) (Delta Ghai) for sucrose solution (10%)

## CHAPTER 4 CONCLUSIONS

The conclusions of this study are:

The stainless steel module used for thermal processing runs in the retort avoided reactions with saline solution (5%). A white precipitate, Aluminum Chloride, which was originally formed in the studies by Ghai et al. (2011) when Aluminum of their module reacted with saline solution (5%), was absent in this study.

Temperature profiles obtained from experimental measurements near the top and bottom of the module exhibited a difference in their heating patterns during come-up time. The solution near the bottom of the module heated more slowly than that near the top, giving a temperature difference of about 15 C at the same instance in time.

Pressure profiles predicted from top and bottom temperature profiles, using the mathematical model by Ghai et al. (2011), gave different values at the same instance in time during the come-up period. Ideally, predictions of pressure in the headspace of the module must be similar. However, due to convectonal currents and heating characteristics of the filled food system, temperatures recorded at top and bottom of the module gave two values significantly different from each other. Therefore, owing to the fact that the bottom of the module heated slower than the top, the pressure profile predicted using bottom temperature was consistently lower than that predicted using top temperature.

The above results showed that differences between predicted pressures from top and bottom temperatures by Paluri and differences between measured and predicted pressures by Ghai et al. (2011) followed similar patterns and were of the same order of magnitude. Disagreement between measured and predicted pressures shown by Ghai

et al. (2011) was likely due to the reason that the temperatures used to predict pressures were measured at the bottom of the module, while the measured pressure was generated in response to headspace temperature at the top of the module.

## CHAPTER 5 SUGGESTIONS FOR FUTURE STUDY

In further studies, the following suggestions could be adapted:

The wireless pressure probe from studies by Ghai et al. (2011) could be used for measuring pressures in real-time. The measured pressures could be compared with predicted pressures from the top and bottom temperatures in the module to determine the optimum location of the thermocouple. Accurate predictions of pressures could be made from mathematical model by Ghai et al. (2011) using temperatures measured at this optimum location. Unfortunately, there was no access to such a probe in present studies.

It is also proposed that in follow-up work, more headspace could be maintained in the rigid pressure-tight module to be able to insert a pressure probe in the headspace and clearly monitor the internal pressure build-up due to expansion of gases in the ample headspace.

Another suggestion is that the Norrish' equation may be used to account for a lower predicted pressure during holding time in case of saline solution and sucrose solutions. This equation may be used to calculate the water activity for non-ideal systems like saline and sucrose solutions. Since the water activity of these solutions is not equal to mole fractions of water, the Norrish' equation can be used as a correction factor for predicting gas pressures. Alternately, Ross' equation could be used instead of Norrish' equation, depending on what is a better fit to the present mathematical model for predicting internal pressure by Ghai et al. (2011).

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## BIOGRAPHICAL SKETCH

Sravanti Paluri graduated from the University of Mumbai in 2011 with a bachelor's degree in chemical engineering. In Mumbai, she was a part of a yearlong project in food and biochemical engineering which inspired her to pursue food engineering in higher studies. She moved to the University of Florida, Gainesville in the fall of 2011 to obtain a Master of Science degree in chemical engineering, with a minor from the Department of Agricultural and Biological Engineering. She will graduate in December 2012 with a thesis and specialization in food engineering and wants to take up further research work in this area. With academic and hands-on experience in rheology, mechanics, sterilization, science and processing of food, her next step is to become a doctoral candidate at a good university in the United States. She believes her extensive research work, short projects, familiarity with Hazard Analysis and Critical Control Points system, and Better Process Control School certification by the University of California, Davis make her an innovative food engineer.