UNIVERSITY OF BELGRADE - FACULTY OF AGRICULTURE

The Institute for Agricultural Engineering

ORGANIZER

University of Belgrade, Faculty of Agriculture, The Institute for Agricultural Engineering, Belgrade, Serbia

CO-ORGANIZERS

University of Belgrade,
Faculty of Mechanical Engineering,
Department of Agricultural Engineering
Belgrade, Serbia

University of Basilicata,
School for Agricultural, Forestry,
Food and Environmental Sciences,
Potenza, Italy

University of Sarajevo,
Faculty of Agricultural and
Food Sciences,
Sarajevo, Bosnia and Herzegovina

Aristotle University of Thessaloniki,
Faculty of Agriculture,
Thessaloniki, Greece

Vinča Institute for Nuclear Science,
Belgrade, Serbia

The Research Institute for Agricultural Economics and Rural Development,
Bucharest, Romania

Fakultet agrobiotehničkih znanosti Osijek,
Osijek, Croatia

Institute of Agricultural Economics,
Belgrade, Serbia

6th International Symposium Agricultural Engineering

ISAE 2023 - PROCEEDINGS

The 6th International Symposium on Agricultural Engineering

Balkan Environmental Association
B.EN.A.

RebResNet
Science through network

Република Србија
МИНИСТАРСТВО НАУКЕ,
ТЕХНОЛОШКОГ РАЗВОЈА И ИНОВАЦИЈА

AMAPSEEC
Association for Medicinal and Aromatic Plants of Southeast European Countries

ISAE 2023
BELGRADE, SERBIA
19th-21st October 2023

ISAE 2023 - Proceedings

The 6th International Symposium on Agricultural Engineering - ISAE 2023
19th - 21st October 2023, Belgrade, Serbia

Belgrade 2023.

ISAE 2023 - Proceedings

The 6th International Symposium on Agricultural Engineering - ISAE 2023

Editors:
Dr. Ivan Zlatanović
Dr. Nedžad Rudonja

Publisher:
University of Belgrade - Faculty of Agriculture
Nemanjina 6, Belgrade-Zemun, Serbia

Publisher representative:
Prof. Dr. Dušan Živković

Editor in chief:
Doc. Dr. Tamara Paunović

Publishing office:
Printing Service of the Faculty of Agriculture
Nemanjina 6, Belgrade-Zemun, Serbia

Edition:
First

Number of e-copies:
100 copies

The publication of ”ISAE 2023 - Proceedings” was approved for The 6th International Symposium on Agricultural Engineering by the decision no. 231/23 from 12.12.2023. year of the Committee for publishing activities of the Faculty of Agriculture, University of Belgrade.

ISBN 978-86-7834-427-5

Belgrade 2023.

ISAE 2023 - Proceedings

The 6th International Symposium on Agricultural Engineering - ISAE 2023
19th - 21st October 2023, Belgrade, Serbia.
www.isae.agrif.bg.ac.rs

ORGANIZER:
University of Belgrade - Faculty of Agriculture
Institute for Agricultural Engineering, Belgrade, Serbia

CO-ORGANIZERS:
University of Belgrade - Faculty of Mechanical Engineering, Belgrade, Serbia

University of Basilicata, School for Agricultural, Forestry,
Food and Environmental Sciences, Potenza, Italy

University of Sarajevo, Faculty of Agricultural and Food Sciences,
Sarajevo, Bosnia and Herzegovina

Aristotle University of Thessaloniki, Faculty of Agriculture, Thessaloniki, Greece

Vinča Institute for Nuclear Science, Belgrade, Serbia

The Research Institute for Agricultural Economics and Rural Development, Bucharest, Romania

Fakultet agrobiotehničkih znanosti Osijek, Osijek, Croatia

Institute of Agricultural Economics, Belgrade, Serbia

INTERNATIONAL SUPPORT:
Scientific Research Platform - GEA (Geo Eco-Eco Agro)
www.geasci.org

Association for Medicinal and Aromatic Plants
of Southeast European Countries - AMAPSEEC
www.amapseec.com

Balkan Environmental Association - BENA
www.benaweb.gr

Research Network on Resources Economics and Bioeconomy - RebResNet
www.rebresnet.eu

SUPPORT BY:
Government of Republic of Serbia
Minister of Science, Technological Development and Innovation
www.nitra.gov.rs

ISAE 2023 - SCIENTIFIC COMMITTEE:

Ivan Zlatanović (Serbia) - president
Biljana Bošković (Serbia) - secretary

Pietro Picuno (Italy)
Dina Statuto (Italy)
Carmela Sica (Italy)
Selim Škaljić (Bosnia and Herzegovina)
Nermin Rakita (Bosnia and Herzegovina)
Chryssoula Nikita-Martzopoulou (Greece)
Thomas Kotsopoulos (Greece)
Vasileios Firfiris (Greece)
Anastasia Martzopoulou (Greece)
Miran Lakota (Slovenia)
Darko Goričanec (Slovenia)
Ivan Plaščak (Croatia)
Danijel Jug (Croatia)
Igor Kovačević (Croatia)
Silvio Košutić (Croatia)
Laszlo Mago (Hungary)
Juraj Šebo (Slovakia)
Kai J. Tiedemann (Germany)
Kurt Tomantschger (Austria)
Mehmet Musa Ozcan (Turkey)
Sekar Subramani (India)
Ronaldo Luiz Mincato (Brazil)
Velibor Spalević (Montenegro)
Zoran Dimitrovski (North Macedonia)
Vili Dragomir (Romania)
Steliana Rodino (Romania)
Miloš Pajić (Serbia)
Kosta Gligorević (Serbia)
Milan Dražić (Serbia)
Zoran Mileusnić (Serbia)
Rajko Miodragović (Serbia)
Rade Radojević (Serbia)
Aleksandra Dimitrijević (Serbia)
Milovan Živković (Serbia)
Mićo Oljača (Serbia)
Vladimir Pavlović (Serbia)
Željko Dolijanović (Serbia)
Đorđe Moravčević (Serbia)
Vlade Zarić (Serbia)
Sanjin Ivanović (Serbia)
Nebojša Nedić (Serbia)
Dragan Marković (Serbia)
Vojislav Simonović (Serbia)
Nedžad Rudonja (Serbia)
Miloš Banjac (Serbia)
Milan Gojak (Serbia)
Marko Jarić (Serbia)
Marija Petković Benazzouz (Serbia)
Saša Barać (Serbia)
Milivoj Radojčin (Serbia)
Ivan Pavkov (Serbia)
Ondrej Ponjičan (Serbia)
Jelena Janevski (Serbia)
Nataša Ljubičić (Serbia)
Valentina Turanjanin (Serbia)
Biljana Vučićević (Serbia)
Jonel Subić (Serbia)
Nataša Soldat (Serbia)
Stevan Čanak (Serbia)

ISAE 2023 - ORGANIZING COMMITTEE:

Miloš Pajić (Serbia) - president
Milan Šunjevarić (Serbia) - secretary

Kosta Gligorević (Serbia)
Milan Dražić (Serbia)
Zoran Mileusnić (Serbia)
Milovan Živković (Serbia)
Rade Radojević (Serbia)
Rajko Miodragović (Serbia)
Goran Topisirović (Serbia)
Olivera Ećim-Đurić (Serbia)
Dragan Petrović (Serbia)
Vladimir Pavlović (Serbia)
Nikola Ivanović (Serbia)
Nataša Milosavljević (Serbia)
Mihailo Milanović (Serbia)
Biljana Bošković (Serbia)
Andrija Rajković (Serbia)
Vojislav Simonović (Serbia)
Nedžad Rudonja (Serbia)
Ivan Zlatanović (Serbia)
Valentina Turanjanin (Serbia)
Milica Mladenović (Serbia)
Biljana Vučićević (Serbia)
Jonel Subić (Serbia)
Maša Buđen (Serbia)
Pietro Picuno (Italy)
Nermin Rakita (Bosnia and Herzegovina)
Vasileios Firfiris (Greece)
Jovana Rakićević (Serbia)
Ivan Plaščak (Croatia)

Preface

Welcome to the 6^{th} International Symposium on Agricultural Engineering, a milestone event in our decade-long journey of advancing agricultural innovation. This Proceedeings encapsulates the essence of our ongoing commitment to exploring and sharing cutting-edge developments in the field of agricultural engineering.

Over the past ten years, our symposium has evolved into a vital platform for researchers, practitioners, and experts from around the world to converge, exchange ideas, and foster collaborations. It is within this collaborative spirit that this compilation of abstracts finds its purpose.

Within these pages, you will discover a diverse array of research, insights, and innovations that span the breadth of agricultural engineering. From precision farming and sustainable practices to the integration of digital solutions and robotics, these abstracts showcase the collective efforts to address the challenges and opportunities facing modern agriculture.

We would like to extend our heartfelt gratitude to all the authors who contributed their research and insights to this book. Your dedication to advancing agricultural engineering is commendable, and your contributions form the foundation of this symposium's success.

As we embark on this 6^{th} edition of our symposium, we look forward to the discussions, debates, and discoveries that will undoubtedly shape the future of agriculture. Together, let us continue to sow the seeds of innovation and cultivate a brighter and more sustainable agricultural landscape.

Thank you for being a part of the 6^{th} International Symposium on Agricultural Engineering.

Prof. Dr. Ivan Zlatanović
ISAE 2023 Scientific Committee President

Contents

ISAE 2023

The 6th International Symposium on Agricultural Engineering, 19th – 21st Oct 2023, Belgrade–Zemun, Serbia

DIMENSIONING AND ASSEMBLYING OF BRAZED ALUMINIUM HEAT EXCHANGER FOR NEEDS OF AGRICULTURAL PROCESS PLANTS

Marko S. Jarić,
Innovation Center of the Faculty of Mechanical engineering in Belgrade
Sanja Z. Petronić,
Institute of General and Physical Chemistry in Belgrade
Nikola J. Budimir,
Innovation Center of the Faculty of Mechanical engineering in Belgrade
Suzana R. Polić
National museum of Serbia
Nedzad Rudonja
Faculty of Mechanical engineering University of Belgrade

Abstract (bold). *Heat exchangers used in agricultural processes are mainly manufactured by three technologies: brazed copper-brass, mechanically assembled aluminum and brazed aluminum. The appropriate choice depends on various criteria: price, weight, corrosion resistance, performance in a limited volume, required pressure drops, temperature resistance, reliability, etc. Brazed aluminum is increasingly popular due to several advantages, such as resistance to high pressure and temperatures. Aluminum heat exchangers can be exposed to external and internal corrosion in various environmental conditions. Corrosion has a negative impact on the mechanical integrity and thermal performance of heat exchangers. Therefore, specific operating design parameters, as well as mechanical design characteristics, are of great importance for consideration in construction. Proper selection and design can ensure the successful and safe operation of the heat exchanger and the plant itself. The HVAC industry is directed towards the search for the best solutions in order to increase the performance, energy efficiency and durability of the equipment while reducing the costs of their production. Aluminum pipes and other aluminum components are increasingly replacing copper pipes. In this paper, application, design, assembling process and operation considerations for brazed aluminum heat exchangers used for needs in agricultural processes have presented.*

Key words (bold): *HVAC, heat exchanger, aluminum, dimensioning, agriculture*

1. INTRODUCTION

Heat exchangers used in agricultural processes are mainly produced by three technologies: brazed copper-brass, mechanically assembled aluminum and brazed aluminum. The appropriate choice depends on various criteria: cost, weight, corrosion resistance, performance in limited volume, required pressure drops, temperature resistance, reliability, etc [1]. For years, aluminum (Al) and aluminum alloys have been used as heat exchanger tube materials due to their low density, good thermal conductivity, and satisfactory mechanical properties suitable for heat exchangers [2, 3]. As the pipe becomes thinner, corrosion resistance has a greater effect [4]. Brazed aluminum is increasingly popular due to several advantages, such as resistance to high pressure and temperatures, one of the reasons being fattening in order to reduce fuel consumption [1].

Brazed aluminum heat exchangers are designed and manufactured according to pressure equipment standards and need to meet safety requirements related to mechanical design, material, manufacturing, testing and inspection requirements of various standards [5,6]. Brazed aluminum heat exchangers are highly efficient, used for a variety of cryogenic and non-cryogenic heat transfer applications, including industrial gas production, petrochemical applications and agricultural processes. Considering that they have a high surface compactness and excellent heat transfer characteristics, they have an advantage over other traditional heat transfer technologies in the application of non-corrosive liquids and gases [7]. Research has shown that the rate of heat transfer in residential air conditioners is 50% higher than the rate of conventional heat exchangers [8].

Taking into consideration the fact that heat exchangers fabricated from aluminum much less represented in agricultural industry such as and problems related to their dimensioning have not been sufficiently explored, hence and the main goals of this paper is mechanical calculations of metal elements of one very specific construction of heat exchanger of which has been fabricated from SB-209-5083-0 material. Beside with the previously mentioned in this paper is also given and methodology of merging of elements of this apparatus with relevant brazing (welding) parameters.

2. STRENGTH CALCULATION OF THREE HEADER ALUMINUM HEAT EXCHANGER

Full calculation of the heat exchangers before starting its fabrication in the workshops usually consists three following necessary types of calculations: calculation of required thermal power (heat transfer), calculation of pressure drop (for needs of further adopting of pumps) and mechanical or strength calculation of metal elements.

After finishing calculation of required heat transfer and pressure drop and determining required design conditions it is starting phase of strength calculation of all metal elements [9-11]. In this paper, it will presented of dimensioning of aluminum heat exchanger, which is using in agricultural engineering. The required design conditions have shown in the Table 1.

For needs of performing strength, calculations and analysis of place installation it was adopted latest edition of ASME Section VIII Division 1 such as relevant standard for this calculation. Review of strength calculations of assembly elements of heat exchanger, which has shown on the picture 1, is in the next lines.

Header 1 thickness:

Minimum required thickness-t_m(according to the ASME Section VIII Division 1-UG-27(c))

$$t_m = \frac{p \cdot R}{S \cdot E - 0.6 \cdot p} + Co = \frac{51.0 \cdot 125}{801 \cdot 0.65 - 0.6 \cdot 51.0} + 0 = 13.01 \text{ mm} < \text{Ta} = 14.31 \text{ mm}$$

where
p=51 Kg/cm^{2}G, design pressure;
R=125 mm, inside radius of header;
S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;
E=0.65, joint efficiency;
Co=0, corrosion allowance;

Header 2 thickness:

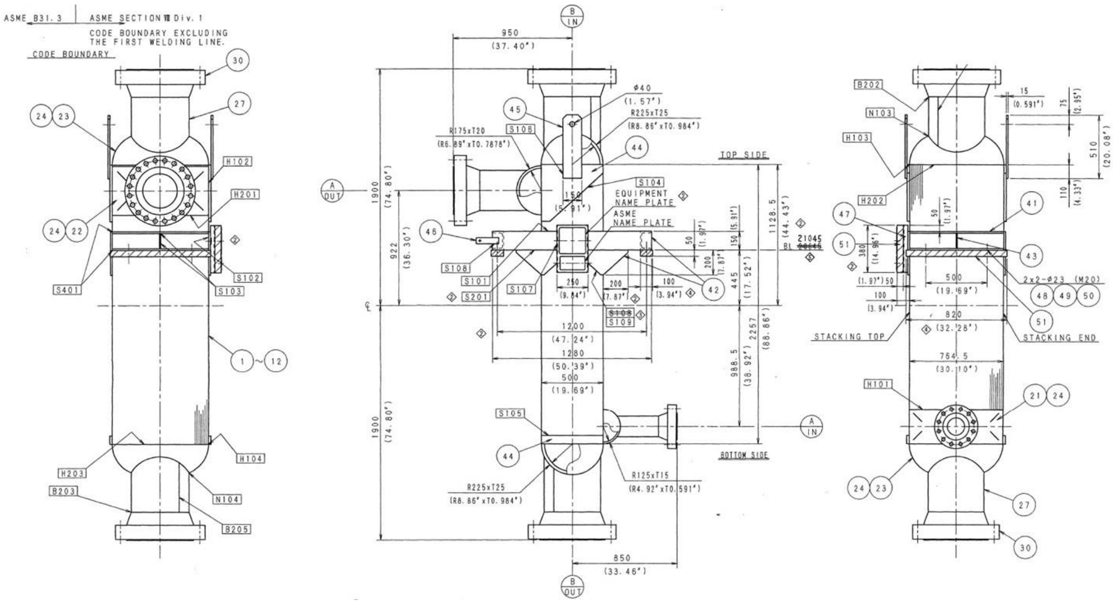
Minimum required thickness-t_m(according to the ASME Section VIII Division 1-UG-27(c))

$$t_m = \frac{p \cdot R}{S \cdot E - 0.6 \cdot p} + Co = \frac{51.0 \cdot 175}{801 \cdot 0.65 - 0.6 \cdot 51.0} + 0 = 18.22 \text{ mm}$$

where
p=51 Kg/cm^{2}G, design pressure;
R=175 mm, inside radius of header;
S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;
E=0.65, joint efficiency;
Co=0, corrosion allowance;

Table 1 Design conditions of brazed aluminum heat exchanger

Stream	-	(A1165)	(B1433)
Fluid	-	Liquified HC	Deethanizer reflux
Design pressure	Kgf/cm^{2}G	51	36.7
	psig	725	522
	barg	50	36
Design temperature	°C	-100÷65	-100÷65
	°F	-148÷149	-148÷149
Hydro test pressure	Kgf/cm^{2}G	66.3	47.8
	psig	942.5	678.6
	barg	65	46.8
Pneumatic test pressure	Kgf/cm^{2}G	-	-
	psig	-	-
	barg	-	-
Air leakage test pressure	Kgf/cm^{2}G	51	36.7
	psig	725	522
	barg	50	36



Picture 1 Construction and dimension of aluminum heat exchanger

Header 3 thickness:

Minimum required thickness-t_m(according to the ASME Section VIII Division 1-UG-27(c))

$$t_m = \frac{p \cdot R}{S \cdot E - 0.6 \cdot p} + Co = \frac{36.7 \cdot 225}{801 \cdot 0.65 - 0.6 \cdot 36.7} + 0 = 16.57 \text{ mm}$$

where

p=36.7 Kg/cm^{2}G, design pressure;

R=225 mm, inside radius of header;

S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;

E=0.65, joint efficiency;

Co=0, corrosion allowance;

Minimum required nozzle thickness (A-in)

(6) Minimum required thickness-tm(according to the ASME Section VIII Division 1-UG-27(c))

$$t_1 = \frac{p \cdot Ro}{S \cdot E + 0.4 \cdot p} + Co = \frac{51.0 \cdot 84.15}{752 \cdot 1.0 + 0.4 \cdot 51.0} + 0 = 5.56 \text{ mm}$$

where

p=51.0 Kg/cm^{2}G, design pressure;

R=84.15 mm, outside radius of pipe;

S=752 kg/cm^2, maximum allowable stress for material SB-209 5083-0;

E=1.0, joint efficiency;

Co=0, corrosion allowance;
(2) The smallest of the following:
(a) the thickness of the cylindrical shell (assuming E=1.0)

$$t_2 = \frac{p \cdot R}{S \cdot E - 0.6 \cdot p} + Co = \frac{51.0 \cdot 125}{801 \cdot 1.0 - 0.6 \cdot 51.0} + 0 = 8.28 \text{ mm}$$

where
p=51 Kg/cm^{2}G, design pressure;
R=125 mm, inside radius of header;
S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;
(b) the minimum thickness of standard wall pipe (STD)

$$t_3 = STD \cdot 0.875 + Co = 7.112 \cdot 0.875 + 0 = 6.23 \text{ mm}$$

The smallest thickness is 6.23 mm
(3) Minimum required thickness-t_m
t_m should be greater value of thicknesses calculated by (1) or (2)
t_m=6.23 mm<t_n·0.875=12.48 mm
where is t_n=14.27 mm-nominal thickness for this pipe;

Minimum required nozzle thickness (A-out)

(6) Minimum required thickness-tm(according to the ASME Section VIII Division 1-UG-27(c))

$$t_1 = \frac{p \cdot Ro}{S \cdot E + 0.4 \cdot p} + Co = \frac{51.0 \cdot 161.9}{752 \cdot 1.0 + 0.4 \cdot 51.0} + 0 = 10.69 \text{ mm}$$

where
p=51.0 Kg/cm^{2}G, design pressure;
R=161.9 mm, outside radius of pipe;
S=752 kg/cm^2, maximum allowable stress for material SB-209 5083-0;
E=1.0, joint efficiency;
Co=0, corrosion allowance;
(2) The smallest of the following:
(a) the thickness of the cylindrical shell (assuming E=1.0)

$$t_2 = \frac{p \cdot R}{S \cdot E - 0.6 \cdot p} + Co = \frac{51.0 \cdot 175}{801 \cdot 1.0 - 0.6 \cdot 51.0} + 0 = 11.59 \text{ mm}$$

where
p=51 Kg/cm^{2}G, design pressure;
R=175 mm, inside radius of header;
S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;
(b) the minimum thickness of standard wall pipe (STD)

$$t_3 = STD \cdot 0.875 + Co = 9.525 \cdot 0.875 + 0 = 8.34 \text{ mm}$$

The smallest thickness is 8.34 mm
(3) Minimum required thickness-t_m
t_m should be greater value of thicknesses calculated by (1) or (2)
t_m=10.69 mm<t_n·0.875=22.22 mm
where is t_n=25.40 mm-nominal thickness for this pipe;

Minimum required nozzles thickness (Bin and Bout)

(6) Minimum required thickness-tm(according to the ASME Section VIII Division 1-UG-27(c))

$$t_1 = \frac{p \cdot Ro}{S \cdot E + 0.4 \cdot p} + Co = \frac{36.7 \cdot 228.5}{801 \cdot 1.0 + 0.4 \cdot 36.7} + 0 = 10.29 \text{ mm}$$

where

p=36.7 Kg/cm^{2}G, design pressure;

R=228.5 mm, outside radius of pipe;

S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;

E=1.0, joint efficiency;

Co=0, corrosion allowance;

(2) The smallest of the following:

(a) the thickness of the cylindrical shell (assuming E=1.0)

$$t_2 = \frac{p \cdot R}{S \cdot E - 0.6 \cdot p} + Co = \frac{36.7 \cdot 225}{801 \cdot 1.0 - 0.6 \cdot 36.7} + 0 = 10.61 \text{ mm}$$

Where

p=36.7 Kg/cm^{2}G, design pressure;

R=225 mm, inside radius of header;

S=801 kg/cm^2, maximum allowable stress for material SB-209 5083-0;

(b) the minimum thickness of standard wall pipe (STD)

$$t_3 = STD \cdot 0.875 + Co = 9.525 \cdot 0.875 + 0 = 8.34 \text{ mm}$$

The smallest thickness is 8.34 mm

(3) Minimum required thickness-t_m

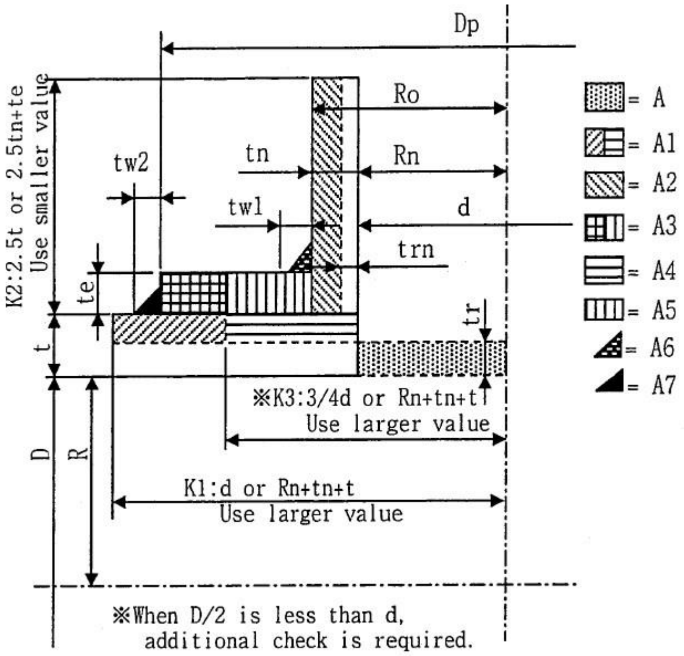
t_m should be greater value of thicknesses calculated by (1) or (2)

t_m=10.69 mm<t_n·0.875=17.50 mm

Where is t_n=20.00 mm-nominal thickness for this pipe;

Together with calculations for headers and nozzles, also calculations of nozzles reinforcement also should be performed especially in case heat exchanger, which are working in high-pressure environment. Taking into consideration that nowadays exist specialized software for this activities in this paper only will be presented nozzle Ain together with its appropriate markings [6, 10 - 12].

One of the most used software, which is using for calculation of pressure equipment elements, is ’’Bend-Tech-Header’’ which enables performing nozzle reinforcement calculations according to the relevant international standard related to pressure equipment. ’’Header software’’ also enables creating 3D-simulations of tube behaviour and bending simulations, which help the fabricator, visualize the bending process before running the part through the part through the machine. This helps to confirm the manufacturability of the part and the bend order [8].

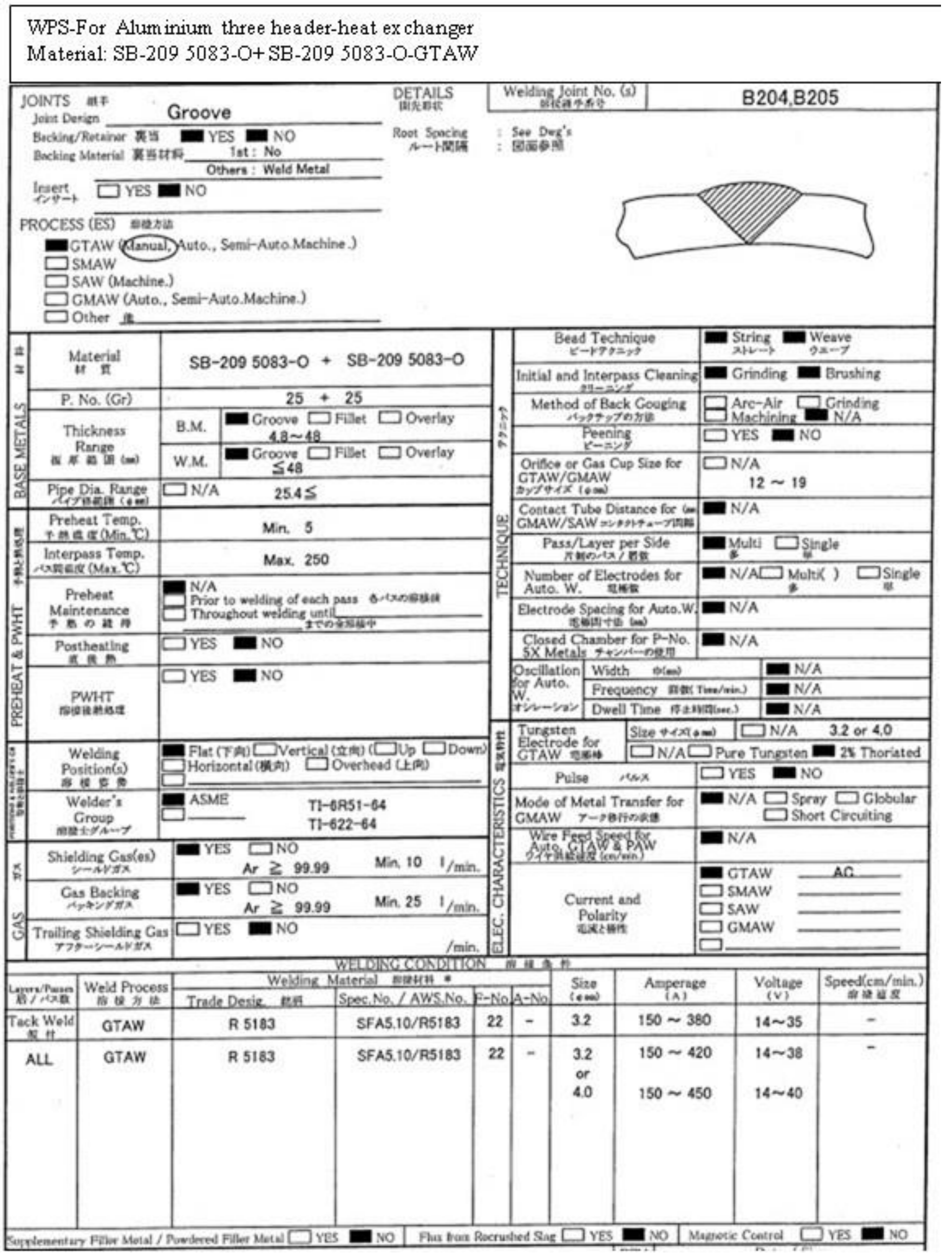


Picture 2 Markings of nozzle reinforcement dimensions

3. MERGING PROCESS OF ALUMINIUM HEAT EXCHANGER

In engineering practice, the working life of a certain apparatus includes the following stages: development, dimensioning and production of technical documentation, apparatus production, and functionality check of apparatus after production, installation of apparatus in a suitable complex system, functionality check after installation, maintenance, etc. After phase of dimensioning respectively creating heat transfer calculations, pressure drop and mechanical calculations, creating welding procedures specifications (WPS) are performing [14].

Creating of WPSs is of exceptional meaning for integrity of apparatus and safety of workers, which are doing maintenance of apparatus during its required working life. This phase is usually carried out in one of two possible ways, either a suitable WPSs are created which are checked and approved, or it is provided appropriate approved WPSs (or standardized WPS-SWPS) from renowned Welding houses. When is in question welding of specific materials (such as aluminium, titanium, magnesium, etc.) often is cheaper and more reliable buying of appropriate WPSs than preparing and approving of their own especially when fabrication companies does not have experienced Welding engineers especially trained for preparation specific WPSs and also when are requiring to performing of destructive examinations of welding samples for needs of qualifying these WPSs. For needs of fabrication, this apparatus appropriate approved WPSs have been provided with GTAW welding process with alternating current polarity.



WPS-For Aluminium three header-heat exchanger
Material: SB-209 5083-O+SB-209 5083-O-GTAW

JOINTS
Joint Design: Groove
Backing/Retainer ☒ YES ☒ NO
Backing Material: 1st : No; Others : Weld Metal
Insert ☐ YES ☒ NO

DETAILS
Welding Joint No. (s): B204,B205
Root Spacing : See Dwg's

PROCESS (ES)
☒ GTAW ([✓ Manual,] Auto., Semi-Auto.Machine.)
☐ SMAW
☐ SAW (Machine.)
☐ GMAW (Auto., Semi-Auto.Machine.)
☐ Other

BASE METALS	Material		SB-209 5083-O + SB-209 5083-O
	P. No. (Gr)		25 + 25
	Thickness Range (mm)	B.M.	☒ Groove ☐ Fillet ☐ Overlay 4.8~48
		W.M.	☒ Groove ☐ Fillet ☐ Overlay ≦48
	Pipe Dia. Range		☐ N/A 25.4≦
PREHEAT & PWHT	Preheat Temp. (Min.℃)		Min. 5
	Interpass Temp. (Max.℃)		Max. 250
	Preheat Maintenance		☒ N/A ☐ Prior to welding of each pass ☐ Throughout welding until
	Postheating		☐ YES ☒ NO
	PWHT		☐ YES ☒ NO
	Welding Position(s)		☒ Flat (下向) ☐ Vertical (立向) (☐ Up ☐ Down) ☐ Horizontal (横向) ☐ Overhead (上向) ☐
	Welder's Group		☒ ASME TI-6R51-64 ☐ TI-622-64
GAS	Shielding Gas(es)		☒ YES ☐ NO Ar ≧ 99.99 Min. 10 l/min.
	Gas Backing		☒ YES ☐ NO Ar ≧ 99.99 Min. 25 l/min.
	Trailing Shielding Gas		☐ YES ☒ NO /min.

TECHNIQUE	Bead Technique	☒ String ☒ Weave
	Initial and Interpass Cleaning	☒ Grinding ☒ Brushing
	Method of Back Gouging	☐ Arc-Air ☐ Grinding ☐ Machining ☒ N/A
	Peening	☐ YES ☒ NO
	Orifice or Gas Cup Size for GTAW/GMAW	☐ N/A 12 ~ 19
	Contact Tube Distance for GMAW/SAW	☒ N/A
	Pass/Layer per Side	☒ Multi ☐ Single
	Number of Electrodes for Auto. W.	☒ N/A ☐ Multi( ) ☐ Single
	Electrode Spacing for Auto.W.	☒ N/A
	Closed Chamber for P-No. 5X Metals	☒ N/A
	Oscillation for Auto. W. – Width	☒ N/A
	Oscillation for Auto. W. – Frequency (Time/min.)	☒ N/A
	Oscillation for Auto. W. – Dwell Time (sec.)	☒ N/A
ELEC. CHARACTERISTICS	Tungsten Electrode for GTAW – Size	☐ N/A 3.2 or 4.0
	Tungsten Electrode for GTAW	☐ N/A ☐ Pure Tungsten ☒ 2% Thoriated
	Pulse	☐ YES ☒ NO
	Mode of Metal Transfer for GMAW	☒ N/A ☐ Spray ☐ Globular ☐ Short Circuiting
	Wire Feed Speed for Auto. GTAW & PAW (cm/min.)	☒ N/A
	Current and Polarity	☒ GTAW AC ☐ SMAW ☐ SAW ☐ GMAW ☐

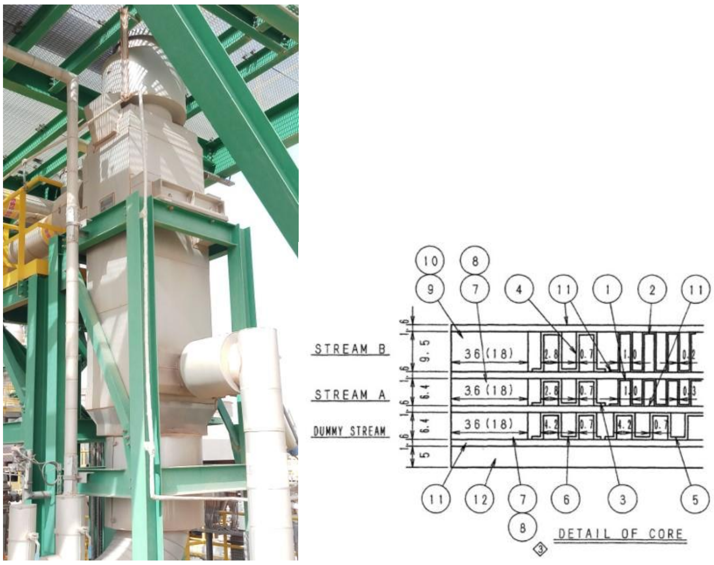
WELDING CONDITION

Layers/Passes	Weld Process	Welding Material				Size	Amperage (A)	Voltage (V)	Speed(cm/min.)
		Trade Desig.	Spec.No. / AWS.No.	F-No	A-No				
Tack Weld	GTAW	R 5183	SFA5.10/R5183	22	-	3.2	150 ~ 380	14~35	-
ALL	GTAW	R 5183	SFA5.10/R5183	22	-	3.2 or 4.0	150 ~ 420 150 ~ 450	14~38 14~40	-

Supplementary Filler Metal / Powdered Filler Metal ☐ YES ☒ NO | Flux from Recrushed Slag ☐ YES ☒ NO | Magnetic Control ☐ YES ☒ NO

Picture 3 Welding procedure specification for aluminium heat exchanger

Here should be mentioned that alternating current has chosen because alternating current provides a cathodic cleaning (sputtering) that removes refractory oxides from the surface of weld joint, which is necessary during welding of aluminium, and magnesium. The cleaning action occurs during the portion of ac wave, when the electrode is positive with the respect to the work piece [15].



Picture 4 Aluminium heat exchanger after installation in plant and shape of internal core

After fabrication of heat exchanger, it were performed necessary non-destructive examinations of the weld joints. On that occasion for checking of surface indications penetrant tests were performed in range of 100% while for checking of volume indications radiography tests were performed in range of 20% for circumferential weld joints and in range of 100% for longitudinal weld joints [16]. Hydro tests of the working spaces have been performed whereby care it was taken regarding the space which is not pressure test in order to increasing pressure in not tested side in sense of avoiding its damaging during external pressure. After finishing all activities, heat exchanger was installed in the agricultural plant, name plate has been attached and insulation on the apparatus has been installed from exterior side (Picture 4). Also, proposed type of maintenance during estimated working life has been adopted according to the relevant international standards for pressure equipment.

4. CONCLUSION

The paper has shown phases of creating process equipment from defining designing conditions up to its installation. Mechanical calculations of specific type of aluminium heat exchanger, which has installed in agricultural process plant has presented which have conducted according to relevant ASME standards. Taking into consideration that selected material for heat exchanger is SB-209 5083-0 appropriate approved welding procedure specification has provided is given in chapter 3 and GTAW-welding process with alternating current has been used for welding activities. After fabrication process dye penetrant tests of weld joints in range of 100% performed for needs of examination of surface defects while for volume defects radiography has been used in range of 100% for longitudinal weld joints and in range 20% for circumferential weld joints. Hydro tests of both working spaces were performed on calculated test pressures and heat exchanger successfully put in service in agricultural plant.

ACKNOWLEDGEMENT

Acknowledgement: This research was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia through contracts Nos. 451-03-47/2023-01/200051, 451-03-47/2023-01/ 200213, 451-03-47/2023-01/200026 and 451-03-47/2023-01/200105.

REFERENCES

1. Paquet, A. (1993) *Comparison of Brazing Processes for Aluminum Heat Exchanger Manufacturing*, SAE Technical Paper 931093. https://doi.org/10.4271/931093.
2. Cavallini, A., Del Col, D., Doretti, L., Matkovic, M., Rossetto, L., Zilio, C. (2005) *Condensation heat transfer and pressure gradient inside multiport mini channels*, Heat Transfer Eng. 26 pp. 45-55.
3. Lacaze, J. , Tierce, S., Lafont, M.C., Thebault, Y., Pébère, N., Mankowski, G., Blanc, C., Robidou, H., Vaumousse, D., Daloz, D. (2005) *Study of the microstructure resulting from brazed aluminum materials used in heat exchanger*, Mater. Sci. Eng. A. 15, pp. 413-414
4. Yong-Sang Kim, In-Jun Park, Byeong-Seon An, Jong Gil Park, Cheol-Woong Yang, Young Hee Lee, Jung-Gu Kim (2020) *Improvement of corrosion penetration resistance for aluminum heat exchanger by alloying zirconium*, Materials Chemistry and Physics, 241, pp. 122275
5. ***EN 13445 Unfired pressure vessels.
6. ***ASME-Boiler and pressure vessels-Section VIII-Division 1-Rules for construction of pressure vessels, July, 2023.
7. Miller, D., Belling, J. (2008*) Application, Design and Operation Considerations for Brazed Aluminum Heat Exchangers in Liquefied Natural Gas Service*, Proceedings of PVP 2008, 2008 ASME Pressure Vessels and Piping Division Conference July 27-31, Chicago, Illinois, USA, PVP2008-61627
8. Webb, R.L., Jung, S.H. (1992) Air-side performance of enhanced brazed aluminum heat exchangers, Ashrae, Atlanta, GA (USA), pp. 91-401.
9. The standards of the brazed aluminum plate-fin heat exchangers manufacturer associations-ALPEMA, 3rd edition, May 2012;
10. Hussain, I., Safety design brazed aluminium heat exchangers to avoid thermal shock, Gas Processing&LNG, 30-November-2012;
11. ***Strength calculation sheet serial number 49C3369 (Revision 2)-Kobe steel, ltd, Japan
12. Jarić, M., Budimir, N., Dobrnjac, M., Bajc, T.,(2015) Cost analysis of heat exchangers with concentric helical tube coils, Proceedings of 6-th International Symposium on Industrial Engineering, SIE 2015, pp. 195-199, ISBN 978-86-7083-864-2,.
13. ***Bend-tech.com/bend-tech-se-software
14. ***Welding procedure specification serial number 262202B-1-Kobe steel, ltd, Japan
15. ***API 577-Welding processes inspection and metallurgy, American Petroleum Institute, October, 2020;
16. ***ASME-Boiler and pressure vessels-Section V-Division 1-Non-destructive examination, July, 2023

ISAE 2023

The 6th International Symposium on Agricultural Engineering, 19th – 21st Oct 2023, Belgrade–Zemun, Serbia

THE EFFECT OF PHASE-CHANGING MATERIAL THICKNESS ON LIGHT CONSTRUCTION BUILDING INDOOR TEMPERATURE

Vučićević S. Biljana[1], Mrdja B. Dragoslav[1], Turanjanin M. Valentina[1], Mladenović R. Milica[1], Škobalj D. Predrag[1]

[1]The University of Belgrade, Vinča Institute of Nuclear Sciences – National Institute of the Republic of Serbia, Laboratory for Thermal Engineering and Energy, Belgrade, Serbia

INVITED PLENARY LECTURE

Abstract. *Due to the excessive use of air conditioners and heating systems, energy consumption by the builiding sector has been growing significantly in recent years, which leads to the accelerated depletion of conventional energy sources and to the fact that renewable energy sources are becoming more and more popular. Phase change materials are suitable for use in latent heat energy storage technology due to their high storage density and stable thermal properties.*

The thickness of phase change materials (PCMs) added to the thermal envelope of a lightweight building is investigated in this study. The simulations were run for 7 days in July, which was determined to be the hottest period of the summer based on the Meteonorm weather file, and when it is difficult to maintain thermal comfort without using a lot of energy. The thermal behavior of the building without PCM and with built-in PCM in the envelope of the building in one wall on the south side and on the ceiling, with different thicknesses of phase-changing material was simulated and the results obtained were analyzed with the aim of establishing which thickness of phase-changing material is optimal for installation in the envelope of the building.

Key words: *Building, PCM, Phase-change material, TRNSYS*

1. INTRODUCTION

A phase is the physical state of a substance, and on Earth matter can exist in solid, liquid, gas, and plasma states. Each type of matter has its own properties, such as specific heat, melting and boiling point.

Heat transfer consists of latent and sensible processes. Latent heat transfer is a phenomenon in which the phase change occurs without any change in the internal temperature. In sensible heat transfer, on the other hand, there is no phase change, but there is a change in the internal temperature.

Phase transition is a physical phenomenon used in applications involving the storage or release of thermal energy (see Fig. 1). The use of phase change materials (PCM) for thermal energy storage is a promising technology based on the principle of latent heat storage of thermal energy. During the charging and discharging process, PCM absorbs or releases significant amounts of energy at a certain temperature due to its high heat of fusion in the phase change temperature range [1] and behaves like a battery that can store and release thermal energy.

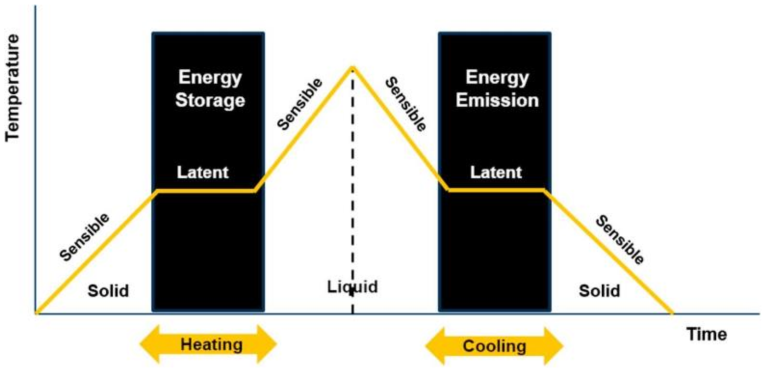


Fig. 1 Schematic diagram of the phase change transition of PCM [1]

The wide range of applications of phase-change materials is related to the temperature range in which the phase transition occurs. There are four basic application groups based on the temperature range. Low-temperature PCMs (-20°C to 5°C) are used in household refrigerators and commercially produced refrigerated goods to cool the products. Medium-low temperature ranges PCM (5°C to 40°C) are used for cooling in free cooling, solar absorption chillers, evaporative and radiant cooling systems, and air conditioning, as well as for passive heating and cooling of buildings. The medium temperature range (40 °C to 80 °C) is used for solar air heaters, solar stills, and solar domestic hot water heating, as well as for cooling electrical equipment. The high temperature range (80 to 200 °C) is used for solar thermal power generation, on-site waste heat recovery, and waste heat recovery for off-site heating purposes [1].

Building envelopes with phase change materials (PCMs) have gained popularity in recent years as an energy-saving option for buildings. This rapidly developing technology has shown that it can significantly improve the energy and thermal performance of buildings, making it an attractive building energy solution [2-4]. As a rapidly evolving technology, PCM has been incorporated into buildings that were still under development, taking into account a variety of factors, including the study of new PCM types, influential positions within the building envelope, optimal quantities, installation methods, and the best passive/active strategies that can be used effectively [5].

The primary purpose of installing PCMs is to increase the heat storage capacity of the building envelope and reduce both indoor temperature fluctuations and energy demand (see Fig. 2) [6]. The amount of latent heat required to cause a phase change in a material is much higher than its specific heat. Therefore, PCM effectively increases the thermal mass of the building material when the temperature rises above or below the PCM transition temperature [7]. PCMs can be broadly categorized according to the changes in their physical state. For building applications, especially for incorporation into walls and wall panels, only solid-liquid PCMs with a certain range of phase change temperatures are used [8]. These PCMs are classified by [9] into three categories: eutectic, inorganic, and organic. The operating temperature range and enthalpy of fusion are different for each group. The ideal properties of PCM for buildings should include: a suitable phase change temperature (18°C–30°C), good heat transfer capabilities, thermal performance stable over time, no overcooling or low undercooling, environmental friendliness, a small volume change during phase transition, and good economics [10,11,12].

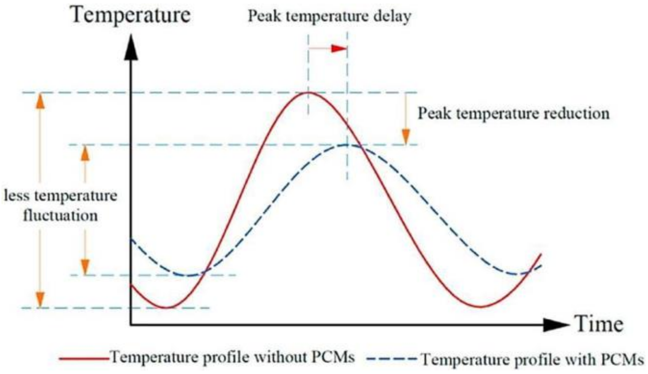


Fig. 2 Indoor temperature of a building with and without the use of PCM [6]

The world is experiencing a constant change in trends in the construction of buildings. The principles of solid construction are increasingly being abandoned in favor of the erection of lightweight building structures suitable for a variety of uses and for extreme weather conditions such as heavy rains, high winds and earthquakes. Lightweight container type objects, for example, can be easily disassembled, relocated, and adapted to a wide variety of needs thanks to their modular design. One of the main disadvantages of lightweight buildings is that they do not have a high thermal capacity, which leads to large fluctuations in indoor temperature with changing outdoor temperatures. The heat capacity of buildings made of lightweight materials can be increased by using phase-change materials (PCM) in the thermal envelope [7].

Recently, a large number of papers have been published on the use of PCM in buildings. For each climate, it is necessary to investigate which phase change material or combination of materials has the greatest effect on reducing energy consumption and payback time [13].

In a paper [14], researchers studied lightweight buildings integrated with phase change material (PCM) to improve the thermal performance of lightweight buildings. EnergyPlus software is used together with a building model validated by experimental data to investigate the improvement of indoor thermal climate with PCM in the five climate zones of China under typical weather conditions. The results show that PCM can effectively control the increase and fluctuation of indoor temperature. For most of the year in temperate regions, PCM can improve the indoor thermal conditions of light buildings.

The study [15] examined the use of bio phase change material (bio-PCM) as a thermal insulation material based on variations in thickness inside a composite wall. Even as the ambient air temperature drops, the PCM wall maintains its thermal inertia for longer periods of time. PCM-incorporated walls were found to be more thermally stable than non-PCM-incorporated walls. The addition of PCM reduces the intensity of temperature variation while also reducing the amplitude significantly. The thickness of bio-PCM can be increased to improve thermal comfort. This behavior suggests that bio-PCM walls can play an important role in maintaining human comfort temperatures in building walls.

The study [5] investigates the optimal thickness of a PCM layer-integrated composite roof under extreme outdoor temperatures. Three different thicknesses of PCM are installed in a residential roof combination in Iraq and compared with a reference roof without PCM. The thermal performance of each PCM layer thickness was evaluated using energy indicators based on room temperature, interior surface temperature, and average exterior surface temperature. Room maximum temperature reduction (RMTR), average temperature fluctuation reduction (ATFR), decrement factor (DF), and time lag (TL) are the indicators under consideration. The study concluded that a thicker PCM layer leads to better thermal performance, as expected. However, the effects of the heat transfer medium PCM and economic considerations should be taken into account when installing a large PCM thickness/quantity in real buildings.

The ability to maintain a certain temperature in buildings as part of thermal comfort, whether those buildings are used exclusively for the storage of goods or for the housing of people or animals, depends largely on the climatic conditions and the materials used for the construction of the thermal envelope. From an architectural point of view, lightweight containers have recently been increasingly used. These buildings have a number of advantages over traditionally built structures, including lower cost, ease of assembly and disassembly, ability to be placed in inaccessible terrain, lack of special permits for placement, and the ability to build a variety of structures for a variety of uses. The lack of such structures is primarily due to their low thermal capacity, which is a prerequisite for maintaining thermal comfort in them without consuming much energy. Phase change materials, as mentioned earlier, can be incorporated into the thermal envelope to increase the thermal capacity of buildings made of lightweight materials. The construction cost will undoubtedly increase due to the installation of phase change materials in the thermal envelope of the building. Therefore, in order to increase the thermal capacity of the building and be economically feasible at the same time, it is necessary to know the physical properties of PCM and the amount that needs to be installed in the walls of the building under certain climatic conditions. This paper deals with the influence of the thickness of PCM introduced into the envelope of the container-type object on the indoor air temperature.

2. MODEL AND TRNSYS SIMULATION

One of the very common objects of light construction that is used for various purposes is the container-type object shown in the fig. 3. This basic type of container was chosen for the analysis of the impact of the installation of different thicknesses of phase-changing material in the thermal envelope of the object with the aim of establishing the relationship between the internal air temperature in the object and the amount of phase-changing material embedded in the thermal envelope.

Fig. 3 Container for people accommodation

Google SketchUp software was used to create the geometric model of this object (Fig.4), which was required in order to simulate the object's thermal behavior. To enter the geometric data into the building model, TRNSYS3d for Google SketchUpTM was used as a plug-in. The thermal performance of the container with one thermal zone is modeled in Type56 modul of the TRNSYS software, a transient systems simulation environment that allows the user to create component-based models to represent energy systems (including localized weather, equipment, building structure, etc.) based on “in actuality” scenarios and then calculate various outputs based on the user's needs.

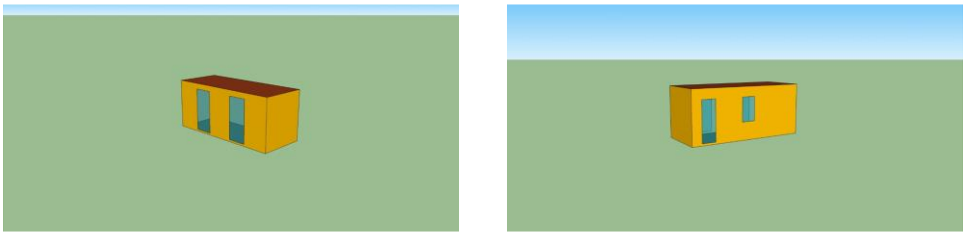


Fig. 4 SketchUp model of container

TRNSYS module Type1270 was used to simulate thermal behavior of a PCM. The phase change material is completely placed inside the envelope, implying that the PCM is not directly adjacent to the zone air. This module interacts with Type56 and models a PCM located anywhere along the thickness of a Type56 wall.

Phase change materials must satisfy a few fundamental requirements in order to be used in construction, including being widely accessible, inexpensive, and non-toxic. For this analysis, coconut oil with latent heats of solidification and melting of 107.34 J/g and 106.17 J/g, respectively, and a phase change temperature between 17.44 and 22.63 °C was used [16].

The density, thermal conductivity, and specific heat of all materials incorporated in the container shell are shown in table 1, and the composition of individual components of the thermal shell: wall, ceiling, and floor are shown in table 2, with layers order shown from the outdoor to the indoor direction. The phase change material is installed in the container's ceiling and south wall panels.

Table 1 Properties of envelope constituent materials

Material	Density (kg/m^3)	Thermal Conductivity (W/mK)	Specific heat (J/kgK)
Steel	7800	15	1800
Mineral Wool	80	0.05	900
PCM-Coconut oil	903	0.321	2900$^{sol.}$/2100$^{liq.}$
Polyurethane	40	0.036	2090
Cement chipboard	1250-1400	0.26	1150

Table 2 Wall, roof and floor layers

Layers	Wall	South Wall	Ceiling	Floor	Direction
Steel thickness (mm)	3	3	3	3	Outdoor
Mineral Wool thickness (mm)	60	60	100	-	
PCM-Coconut oil thickness (mm)	-	0-40	0-40	-	
Polyurethane thickness (mm)	-	-	-	50	↓
Steel thickness (mm)	-	-	-	3	
Cement chipboard thickness (mm)	-	-	-	20	
Steel thickness (mm)	3	3	3	-	Indoor

The simulations were run in the Simulation Studio (fig. 5) software from July 18 to July 25 (for the 4758th to 4926th hour observed since the start of the year), with a simulation step of 5 minutes. We used a weather file that contained data on external meteorological parameters for a typical meteorological year in Belgrade.

Simulations of the thermal behavior of the container without PCM and with various PCM thicknesses were performed by the Simulation Studio of the TRNSYS software package with the aim of analyzing the influence of the thickness of the phase-changing material on the container thermal behaviour by observing the internal air temperature.

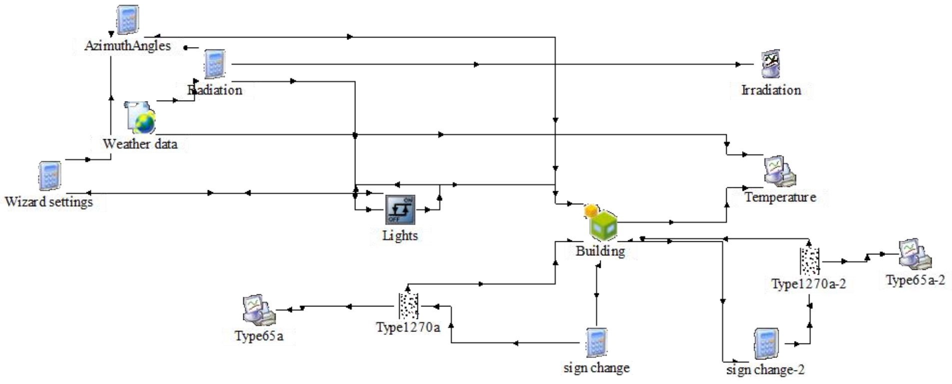


Figure 5 Component layout for a simulation studio

3. RESULTS AND DICUSSION

A simulation of the thermal behavior of the object in the hottest period of July was carried out according to the Meteonorm's weather file for Belgrade in the period from 4758-4926 hours observed since the beginning of the year, with the goal of analyzing the influence of the thickness of the phase-changing material embedded in the thermal envelope of the container, on the internal air temperature. For the phase change material, coconut oil with thermophysical properties suitable for use in the summer was chosen.

The thickness of the phase-changing material installed in the building's ceiling and the wall on the south side of the total area of 30.12m2 was varied in a total of 8 simulations of the container's thermal behavior, ranging from 0.002m to 0.04m. The outcomes of these simulations are shown in Figure 6. One temperature is represented by each curve. A red curve indicates the outside air temperature as reported by the Belgrade weather file. The internal air temperature of a container without a phase change material in its envelope is represented by the light yellow curve. The other curves represent the internal temperature of the air in the container in the following order: gray for a thickness of 0.002m, yellow for a thickness of 0.004m, light blue for a thickness of 0.008m, green for a thickness of 0.012m, purple for a thickness of 0.02m, and black for the largest observed thickness of 0.04m. The installation of phase-changing material significantly reduces the amplitude of the daily temperature change as well as the shift of the temperature peak.

It is clear that even very thin layers of phase-changing material embedded in the envelope can cause a sizable drop in internal air temperature. The internal temperature peak is reduced by about 10 degrees Celsius for the simulation's observed period.

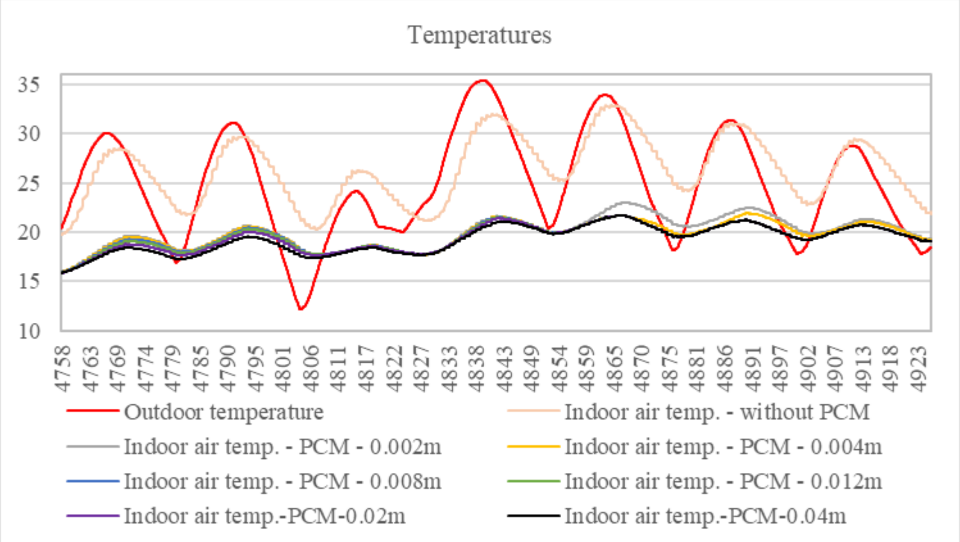


Fig. 6 Indoor and outdoor temperatures

Figure 7 depicts a more detailed view of the second sinusoidal temperature change's peak. Depending on the thickness of the embedded phase change material, the blue circles represent the maximum indoor air temperatures at a time point corresponding to 4794.08 hours from the start of a typical meteorological year. The temperature of the internal air in the container where the phase-changing material is not embedded in the shell is represented by the red circles. The temperature of the indoor air can be reduced by 8.83°C by installing a small thickness of PCM of 0.002m observed for the above-mentioned moment of time. Installing PCM with a thickness of 0.04m reduces the temperature by 9.94°C, so increasing the thickness of PCM from 0.002m to 0.04m reduces the temperature by 1.11°C.

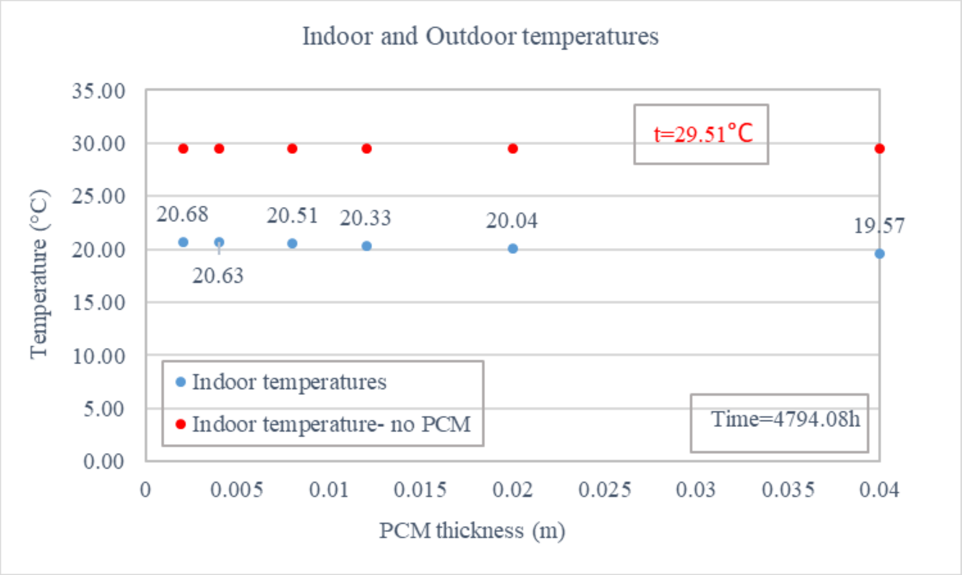


Fig. 7 The internal temperature change as a function of the PCM thickness

Figure 8 depicts a graphical representation of the increase in mass of PCM embedded in the thermal envelope of the container as the thickness increases. When the thickness of PCM material is increased from 0.002m to 0.04m, the mass of PCM increases from 54.4kg to 1087.9kg, or about 20 times, while the indoor air temperature is reduced by 1.11°C. This increase in mass could cause significant problems for container-type facilities in terms of construction and transportation, threatening their primary advantage over traditional construction.

Before installing PCM material, it is necessary to simulate the thermal behavior of the object with all available parameters in order to choose the best combination of PCM type, quantity, and position of the material to be installed for the ambient conditions of a specific geographic location. This is necessary because the need to increase the thermal capacity of light objects must be met in a way that does not endanger their other characteristics.

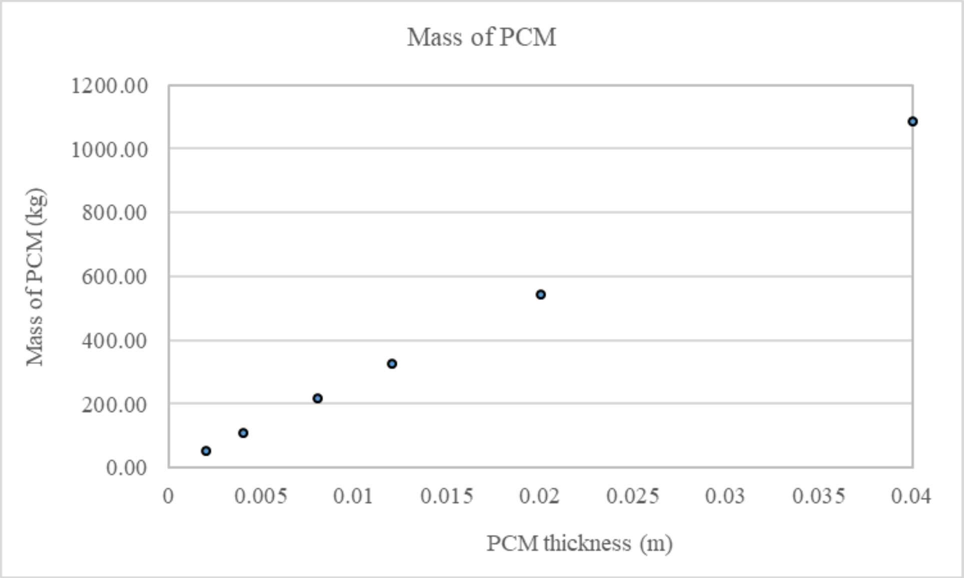


Fig. 8 The relationship between PCM mass and thickness

4. CONCLUSION

This study is based on a simulation of the thermal behavior of a lightweight, container-like object in which a phase-change material was added to the thermal envelope. According to the Meteonorm weather file for Belgrade, the simulation was conducted from July 18 to 25 during the hottest time of the year. Indoor air temperature was simulated for a container-type facility without PCM and a facility with PCM. Coconut oil was added to the sandwich wall panels on the south side of the building, as well as to the ceiling panels, as a phase-changing material, and the thickness of this material was varied from 0.002 to 0.04 meters.

The installation of phase-changing material can lower the internal air temperature and mitigate the sinusoidal daily distribution. Installation of the smallest and largest PCM thicknesses of 0.002 m and 0.04 m, respectively, decreased the indoor air temperature by 8.83 °C and 9.94 °C during the observation period. This increase in thickness resulted in a decrease in the indoor temperature by 1.11°C, but the total weight of the installed PCM increased from 54.4 kg to 1087.9 kg, which is a very negative consequence for lightweight buildings.

These results show that the internal temperatures of a building can be significantly reduced by installing PCM even at very low thicknesses, but an analysis of all the important parameters related to the thermophysical properties of PCM, the environmental conditions of the climate in which they are used, their cost, etc. must be carried out beforehand. A balance must be found between improving the thermal capacity, whose low values are one of the main disadvantages of container-type buildings, and modifying other properties resulting from the addition of PCM to their thermal envelope.

Acknowledgement: *This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia; grant number 451-03-47/2023-01/ 200017.*

REFERENCES

1. Du, K., Calautit, J., Wang, Z., Wu, Y., Liu, H. (2018) *A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges*, Applied Energy, 220 pp. 242-273.
2. Rathore, P. K. S., Shukla, S. K., Gupta, N. K., (2020) *Potential of microencapsulated PCM for energy savings in buildings: A critical review*, Sustainable Cities and Society, 53, pp. 101884.
3. Al-Yasiri, Q, Szabó, M., (2021) *Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis*, Journal of Building Engineering, 36, 102122.
4. Tunçbilek, E., Arıcı, M., Bouadila, S.et al., (2020) Seasonal and annual performance analysis of PCM-integrated building brick under the climatic conditions of Marmara region, Journal of Thermal Analysis and Calorimetry, 141, pp. 613–624.
5. Al-Yasiri, Q, Szabó, M., (2021), *Case study on the optimal thickness of phase change material incorporated composite roof under hot climate conditions*, Case Studies in Construction Materials, 14, e00522.
6. Suresh, C., Hotta, T.K., Saha, S.K. (2022) *Phase change material incorporation techniques in building envelopes for enhancing the building thermal Comfort-A review*, Energy and Buildings, 268, 112225.
7. Roth, K., Westphalen, D., Brodrick, J., (2017) *Technology of phase-changing materials for construction*, KGH – Klimatizacija, grejanje, hlađenje, 36 (4), pp. 31-33 (*in Serbian*).
8. Faraj, K., et al., (2021) *A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications*, Journal of Energy Storage, 33, 102815.
9. Abhat A., (1983) *Low temperature latent heat thermal energy storage: Heat storage materials*, Solar Energy, 30 (4), pp. 313-332.
10. Li, D., Zhuang, B., Chen, Y., Li, B., Landry, V., Kaboorani, A., Wu, Z., Wang, X. A., (2022) *Incorporation technology of bio-based phase change materials for building envelope: A review*, Energy and Buildings, 260, 111920.
11. Junaid, M. F., Rehman, Z., Čekon, M., Čurpek, J., Farooq, R., Cui, H., Khan, I., (2021) *Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications*, Energy and Buildings, 252, 111443.
12. Tyagi, V.V., Chopra, K., Sharma, R.K., Pandey, A.K., Tyagi, S.K., Ahmad, M. S., Sarı, A., Kothari, R., (2022) *A comprehensive review on phase change materials for heat storage applications: Development, characterization, thermal and chemical stability*, Solar Energy Materials & Solar Cells, 234, 111392.
13. Panayiotou, G.P., et al., (2016). *Evaluation of the application of Phase Change Materials (PCM) on the envelope of a typical dwelling in the Mediterranean region*, Renewable Energy, 97, 24-32.
14. Li, Y., Wang, Y., Meng, X., Wanga, M. & Longa, E., (2015) *Research on Indoor Thermal Environment Improvement of lightweight Building Integrated with Phase Change Material Under Different Climate Conditions*, Procedia Engineering, 121, pp. 1628 – 1634.
15. Govindasamy, D., Panwar, V., (2021) *Effect of variation in thickness of phase change material on temperature across the composite building wall*, Materials Today: Proceedings, 46(20), pp. 10221-10226.
16. Alqahtani, T., Mellouli, S., Bamasag, A., Askri, F., & Phelan, P. E. (2020) *Experimental and numerical assessment of using coconut oil as a phase-change material for unconditioned buildings*, International Journal of Energy Research, 44(7), pp. 5177-5196.