



นำผลงานแสดงในงานนิทรรศการร่วมกับบริษัทศรีทิพัฒน์เอนจิเนียริง ที่ ไบเทค บางนา



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สรุปผลการนำเสนอ Microwave Vacuum Dryer (งานสัมมนา16-18 มีนาคม 2552)

รายชื่อบริษัทที่ชมเครื่อง	ผู้ติดต่อ	ธุรกิจของลูกค้า	ระดับความสนใจและข้อคิดเห็นจากลูกค้า	หมายเหตุ
บ.โกลโบ ฟู้ดส์ จำกัด	คุณสมพงษ์ คุ่มภัย ผู้จัดการฝ่ายผลิตสาขา สุพรรณบุรี	-ผงปรุงรส อาหาร -เครื่องแกง -ผลิตภัณฑ์จาก แป้ง -เกล็ดขนมปัง	ลูกค้าค่อนข้างสนใจเพราะสินค้าของทางลูกค้ามีกระบวนการอบแห้งอยู่ในProcess ลูกค้าสอบถามเกี่ยวกับผลกระทบของความร้อนที่เกิดจากMicrowave ต่อproducts เพื่อจุลินทรีย์ต่างๆ ในProducts มีการสอบถามราคาของเครื่องและคิดว่าน่าจะเหมาะกับโปรดัคส์ที่มีมูลค่าสูงและลูกค้ายังให้ความสนใจmicrowave ระบบสายพาน	
บ. Kenmin food.	คุณศรีอนันต์ ผู้ช่วยผู้จัดการแผนกQC.	-เส้นหมี่อบแห้ง	-ลูกค้าสนใจระดับน้อยถึงปานกลางเพราะเคยได้รับความรู้เรื่องนี้มาบ้างแต่กำลังให้ความสนใจกับระบบ continuous line มากกว่า	
บ.ซีพี(แกลง)	คุณสรศักดิ์ มณีกาญจน์ Maneger	-ผลิตภัณฑ์แปรรูปกุ้ง	-ลูกค้าสนใจอยากได้ข้อมูลหากทำการทดสอบกับกุ้งเผื่อจะแปรรูปเป็นกุ้งแห้ง.	
บ.เจริญดี มาร์เก็ตติ้ง	คุณศักดิ์ชัย สามารถ Maneger	-จัดจำหน่าย เม็ดมะม่วงหิมพานต์	-ลูกค้าให้ความสนใจในระดับสอบถามเพื่อเป็นความรู้เฉยๆ	
บ. ACK ไฮโดรฟาร์ม	คุณเกตุกาญดา	-ผลิตภัณฑ์ พืชผักปลอดสารพิษ	-ลูกค้าให้ความสนใจค่อนข้างมากสอบถามเกี่ยวกับระบบการทำงาน, ข้อดีและประสิทธิภาพของเครื่องมีความสนใจที่จะทดสอบกับมะเขือเทศ	
บ.สหกรณ์ กรีนเนท	คุณ บุญจิรา ตันเรือง ผู้จัดการสหกรณ์ กรีนเนท	-สินค้าเกษตรอินทรีย์	-ให้ความสนใจอย่างมากมีความสนใจที่จะลองทดสอบกับผลิตภัณฑ์จำพวก ขิง, ข่า	
บ.สุรพลฟู้ดส์	คุณ มนไท จูพิติตตะ Factory Maneger.	-อาหารแช่แข็ง สุรพลฟู้ดส์	-สอบถามเป็นความรู้เฉยๆ เพราะProcess ของทางลูกค้าเป็นการทอด, ึ่งด้วยsteam และแช่แข็งจึงให้ความสนใจกับระบบนี้ค่อนข้างน้อย	
บ.ไทยนิสชิน เซฟุง จำกัด	คุณธวัชชัย บัวรอด M/T GL	-ซอสสปาเก็ตตี้ แช่แข็ง และพิซซาญี่ปุ่นแช่แข็ง	-ให้ความสนใจในระดับสอบถามความรู้เพิ่มเติม	
บ.ท่าเรือฟู้ดส์ จำกัด	คุณ ธีรวุฒิ วุฒิชาติ Engineer	-อาหารทะเลแช่แข็ง	-ให้ความสนใจในระดับสอบถามเป็นความรู้เพิ่มเติมเพราะProcess ของทางลูกค้าเป็นการึ่งด้วยsteam	
บ.ไทยเพรซิเดนท์ฟู้ดส์	คุณวิชาญ ปาตาล		-ให้ความสนใจในระดับสอบถามเป็นความรู้	

จำกัด(มหาชน)	รองหัวหน้าแผนก		เพิ่มเติม	
รายชื่อบริษัทที่ชมเครื่อง	ผู้ติดต่อ	ธุรกิจของลูกค้า	ระดับความสนใจและข้อคิดเห็นจากลูกค้า	หมายเหตุ
บ.ลำปะหลังพัฒนา จำกัด	คุณ ธนาวัฒน์ สุวรรณ รุ่งเรือง	-ทำแบ่งจากมัน ลำปะหลัง	- มีความสนใจที่จะทดสอบกับแป้งเพราะต้องการ ใช้เป็นอุปกรณ์ใน Lab	
บ.เรืองแผนไทยเภสัช	คุณเรืองยศ เลิศสุขุมวณิช เจ้าของกิจการ	-ยาจาก สมุนไพรโบราณ	-มีความสนใจเป็นอย่างมากเพราะมีความต้องการ ให้สารเคมีในตัวยาไม่สูญหายไปเนื่องจาก กระบวนการอบแห้ง	

สรุปผลที่ได้จากงานสัมมนาในครั้งนี้

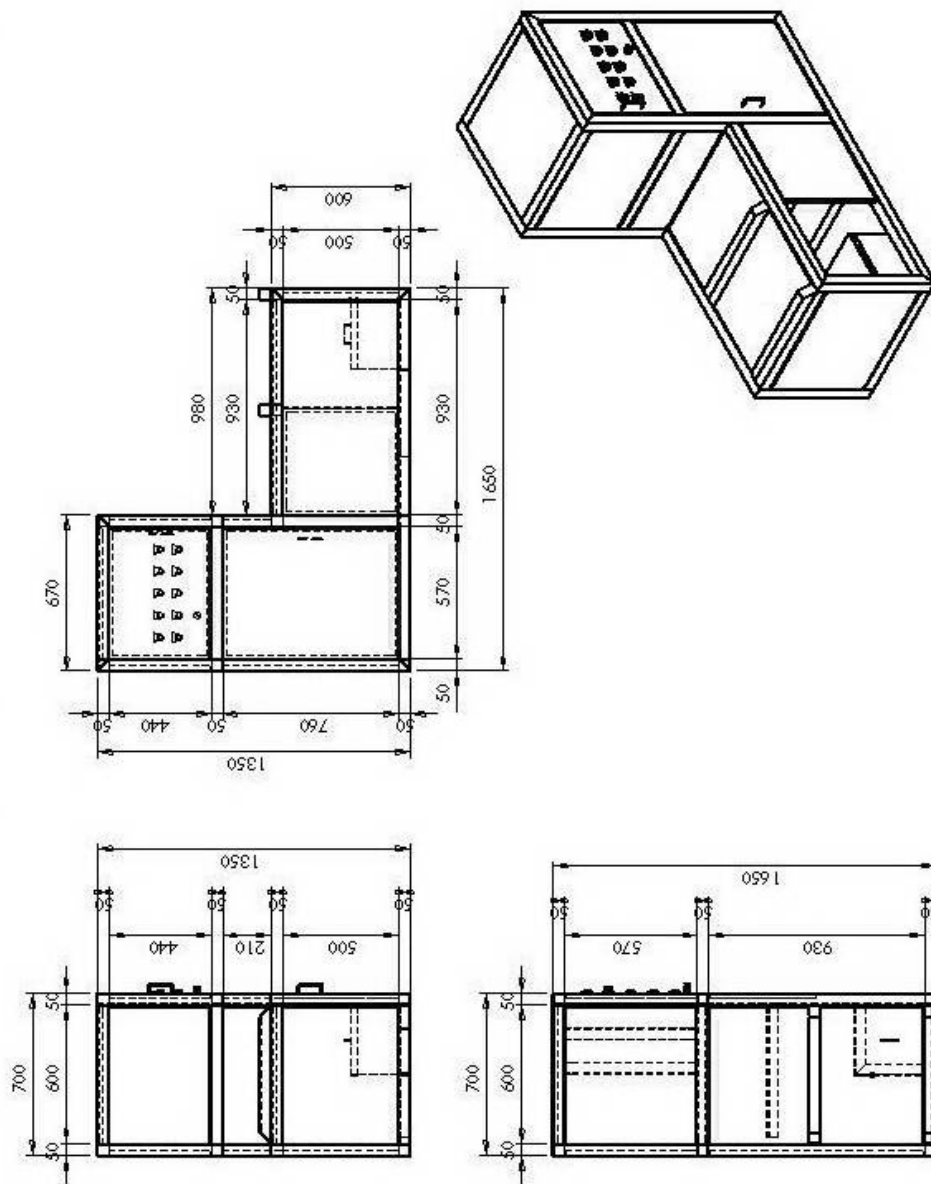
- 1.เป็นที่สนใจกับกลุ่มลูกค้าที่ประกอบการเกี่ยวกับพืชผลทางการเกษตรมากที่สุด
- 2.ความสนใจของลูกค้าในตัวเครื่องมากขึ้นขึ้นอยู่กับกระบวนการผลิตของทางลูกค้าว่ามีกระบวนการอบแห้งอยู่ในสายการผลิตหรือไม่หากมีอยู่ก็จะให้ความสนใจเป็นอย่างมากแต่หากไม่มีก็จะสอบถามเล็กน้อยพอเป็นเกร็ดความรู้เพิ่มเติม.
- 3.กลุ่มลูกค้าบางกลุ่มก็เคยเจอหรือเคยอบรมความรู้เรื่องนี้มาบ้างพอสมควรจึงให้ความสนใจกับระบบ Continuous line มากกว่า.

ข้อเสนอแนะ

- 1.หากมีการแนะนำหรือเกริ่นนำในช่วงสัมมนาให้ลูกค้ารับทราบน่าจะชักจูงให้ลูกค้าสนใจมากขึ้นกว่านี้.
- 2.ลูกค้าหลายรายเฝ้ารอที่จะชมระบบการอบแห้งด้วย Microwave ที่เป็น Continuous line ในงาน THAI FEX.

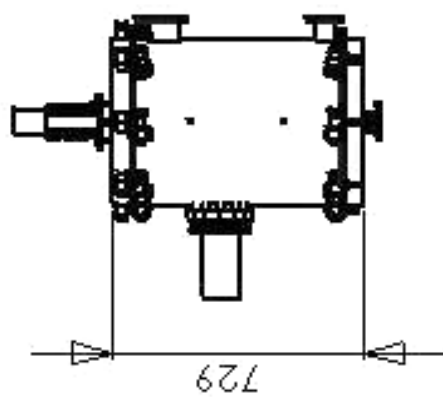
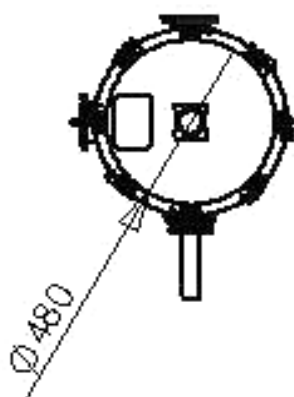
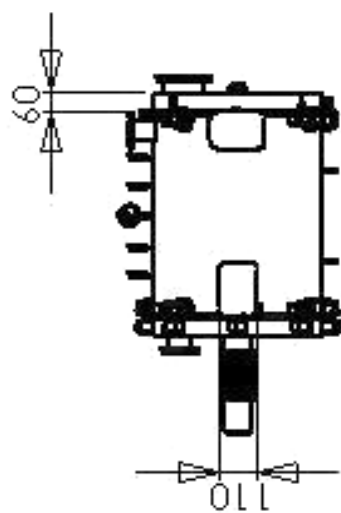
กฤษณะเทพ แก้วเขียว / เสกสม จันทน์ภาววรรณ.

แบบวาด (Drawing) ของอุปกรณ์ต่าง ๆ ในการสร้างเครื่องอบแห้งอเนกประสงค์
เชิงพาณิชย์โดยใช้ไมโครเวฟร่วมกับระบบสุญญากาศ (บางส่วน)

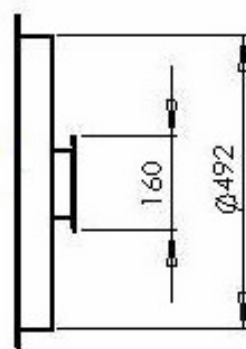
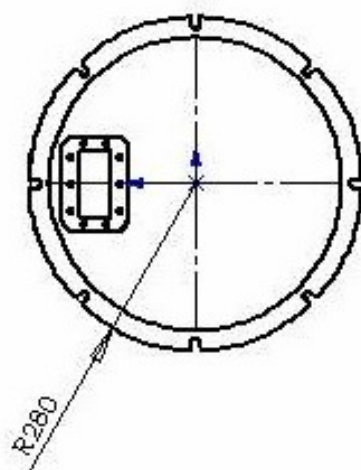
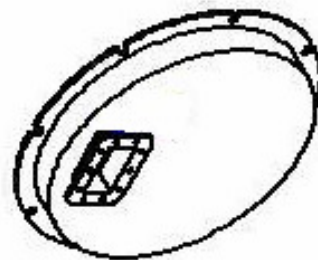
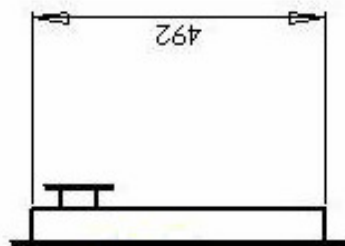


ภาพที่ 1

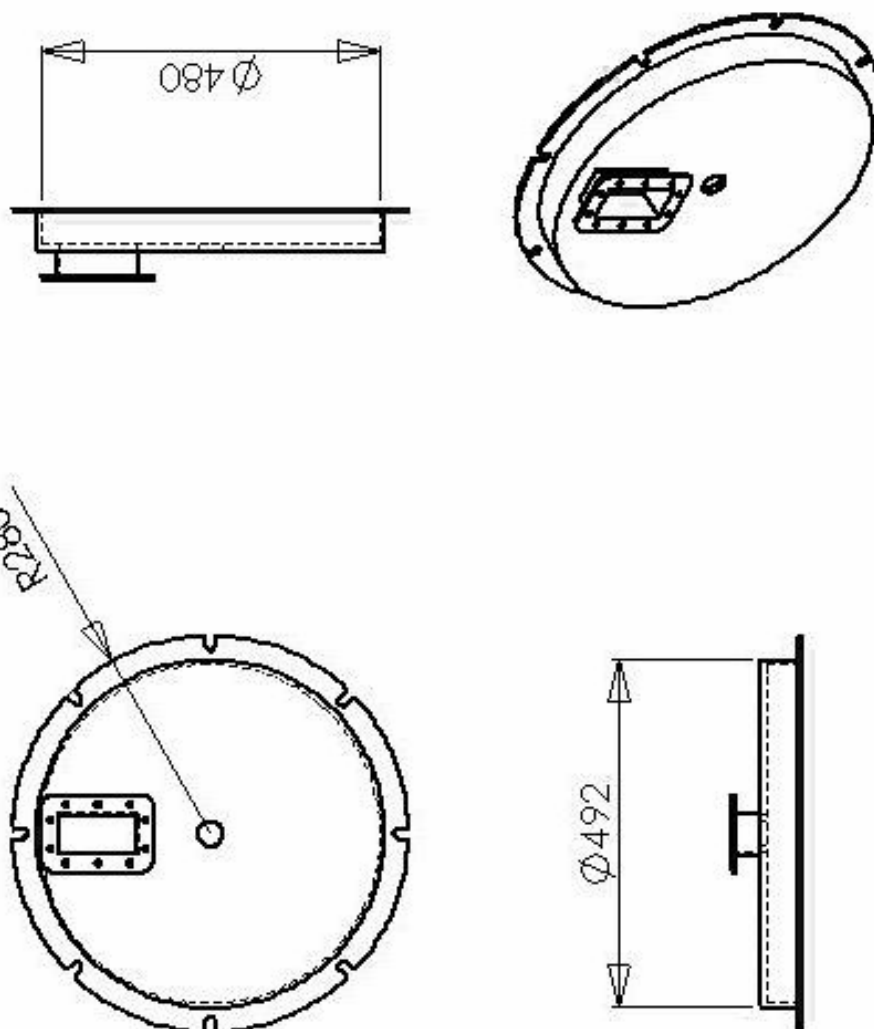
แบบวาดโครงของเครื่องอบแห้ง



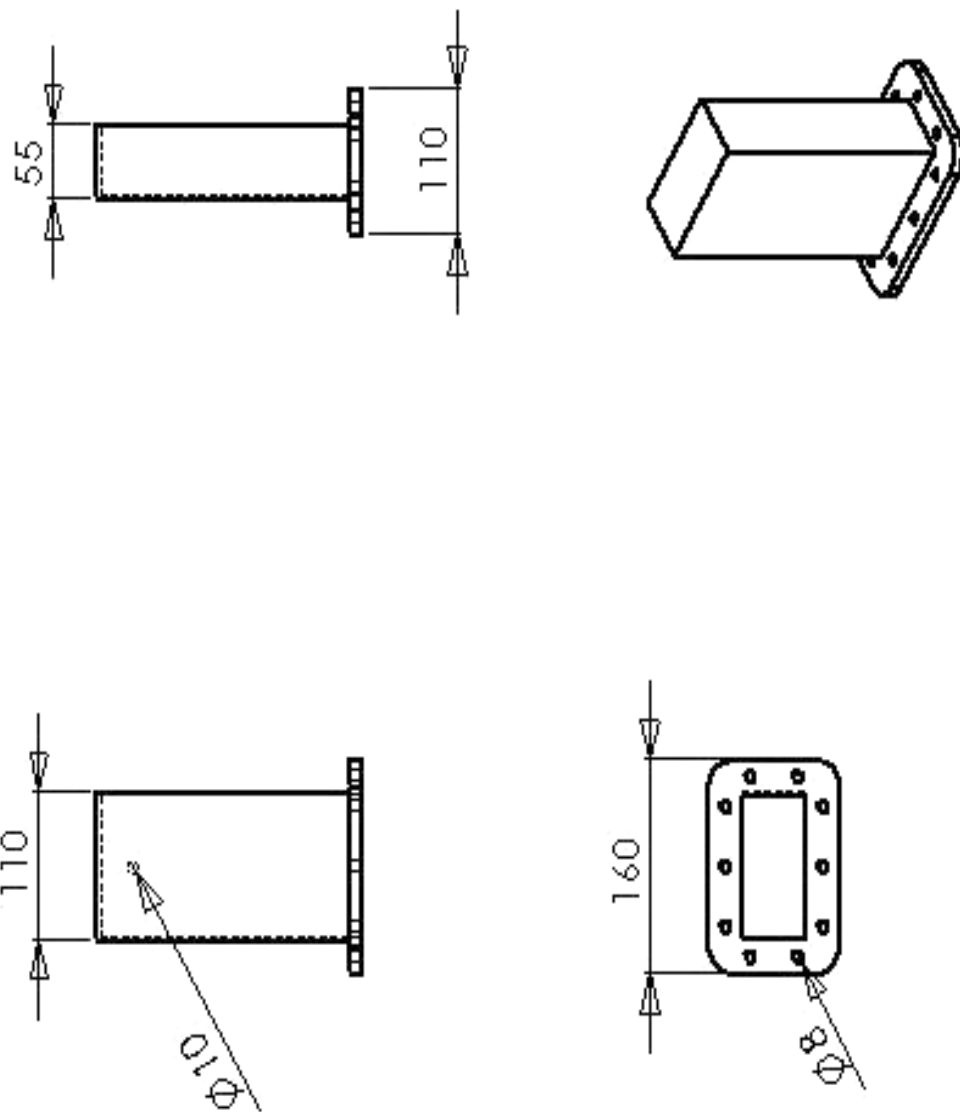
ภาพที่ 2
แบบวาดค่าวัดของเครื่องอบแห้ง



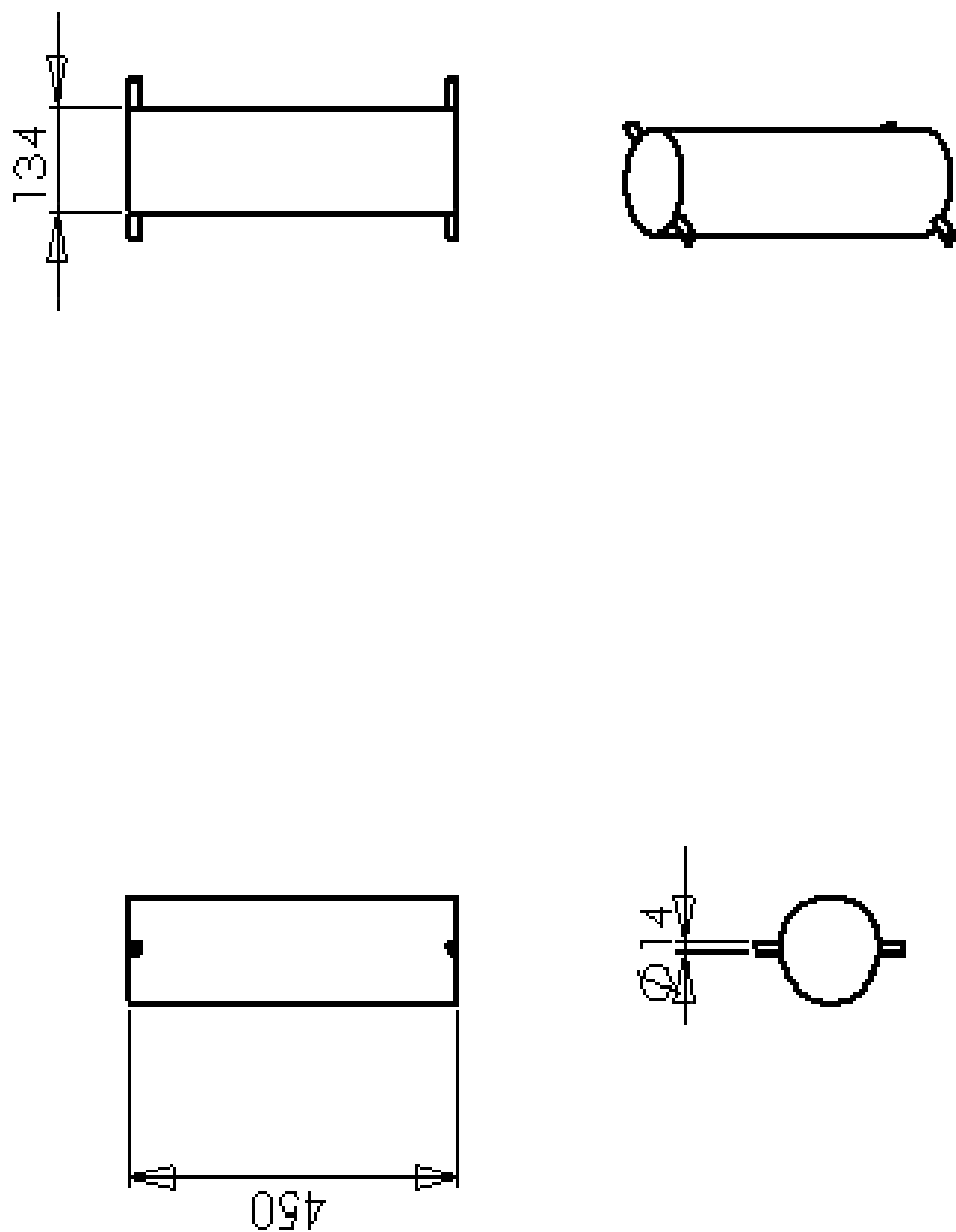
ภาพที่ 3
แบบวาดฝาควิตู้ด้านหน้า



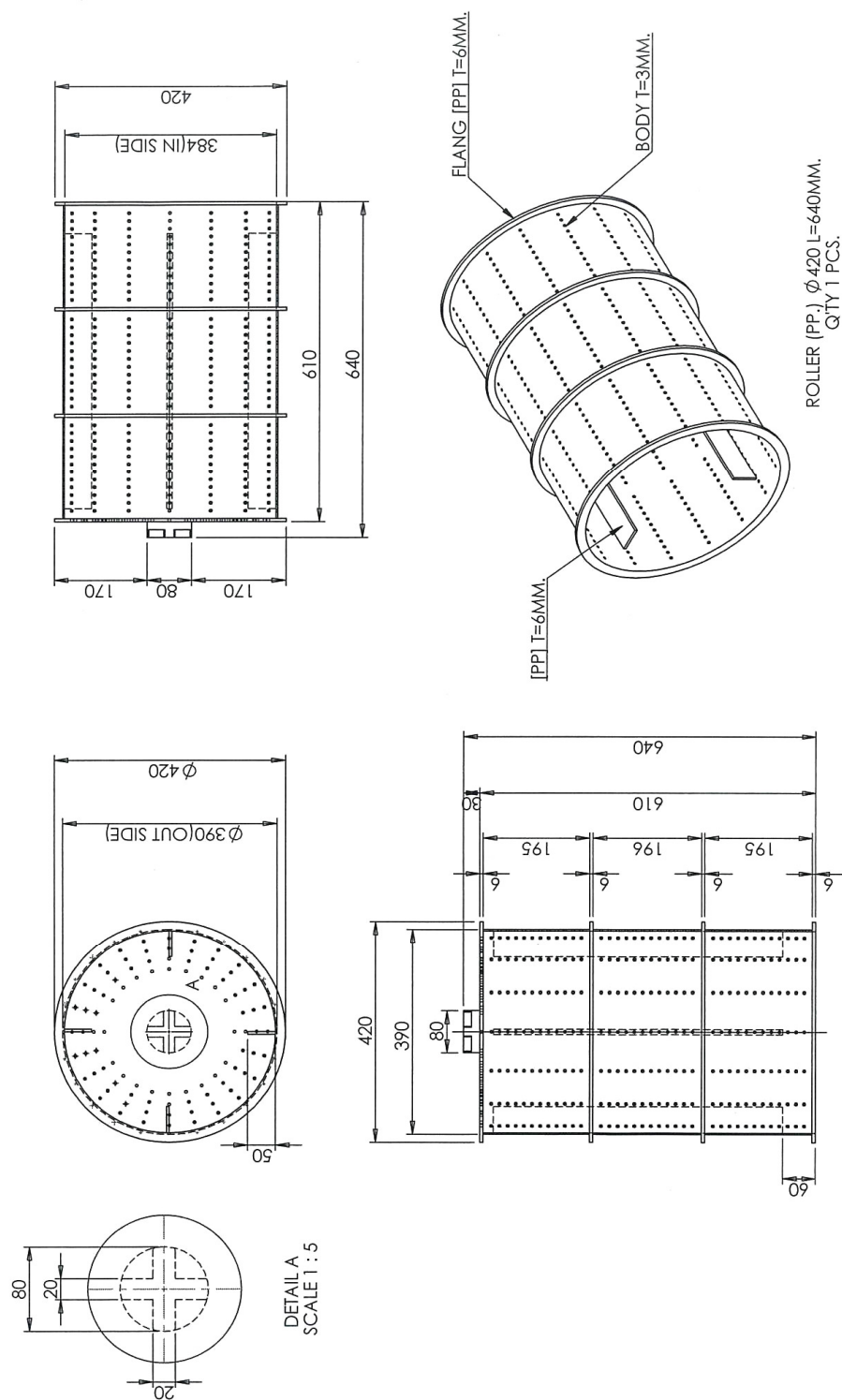
ภาพที่ 4
แบบวาดฝาควิตู้ด้านหลัง



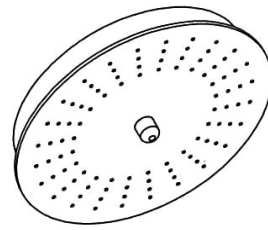
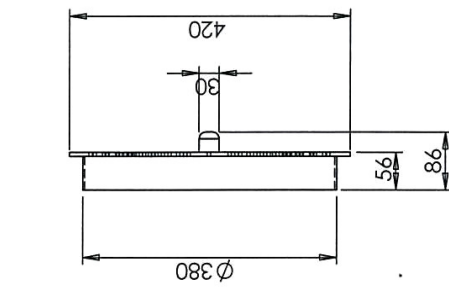
ภาพที่ 5
แบบวาดท่อนำคลื่น



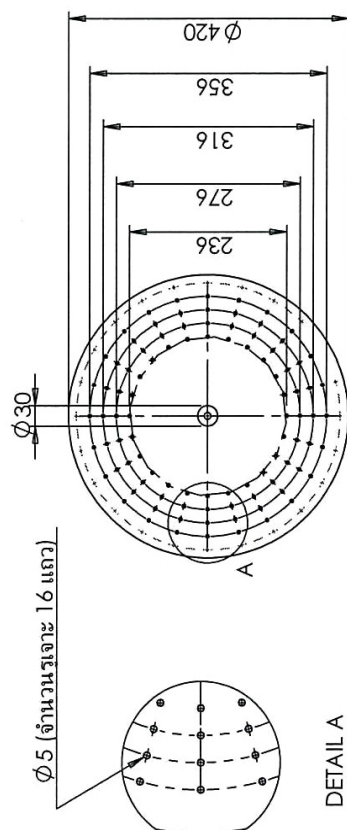
ภาพที่ 6
แบบวาดถังควบแน่น



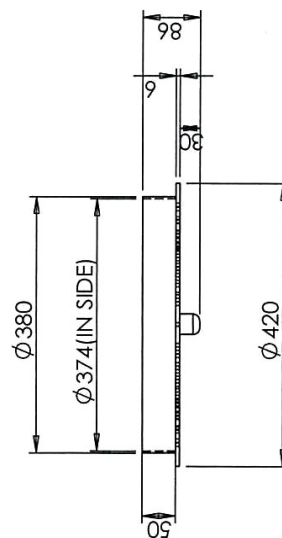
ภาพที่ 7
แบบวาดถังหมุน (PP-Rotary Drum)



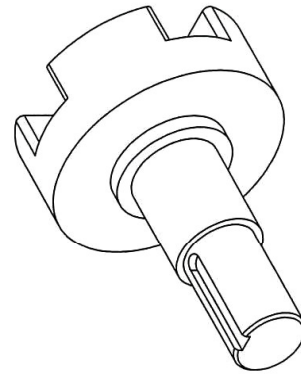
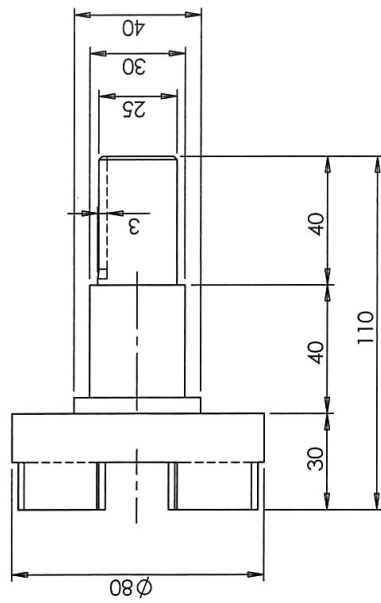
COVER [PP] Ø 420MM.
QTY 1 PCS.



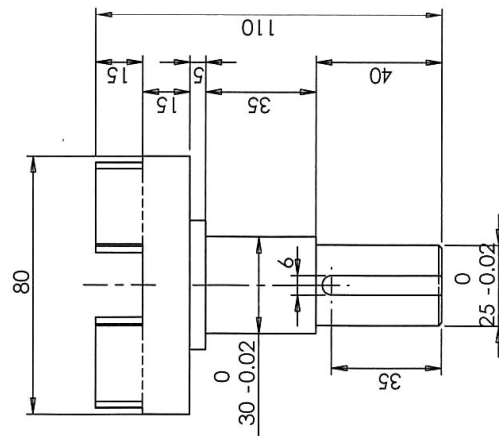
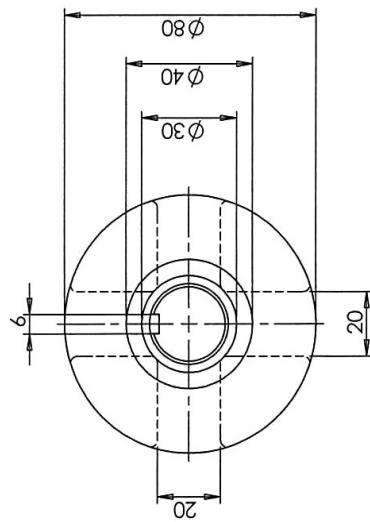
DETAIL A
SCALE 1 : 5



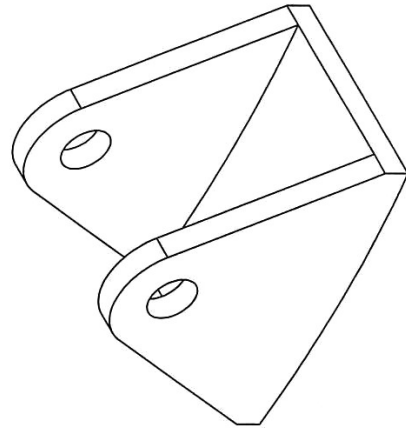
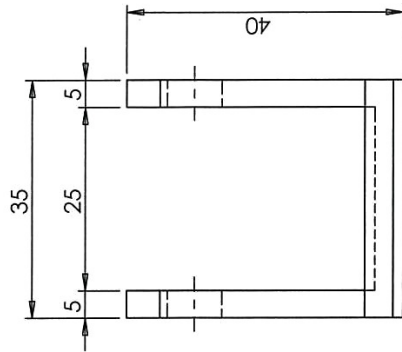
ภาพที่ 8
แบบวาดฝาถังหมุน



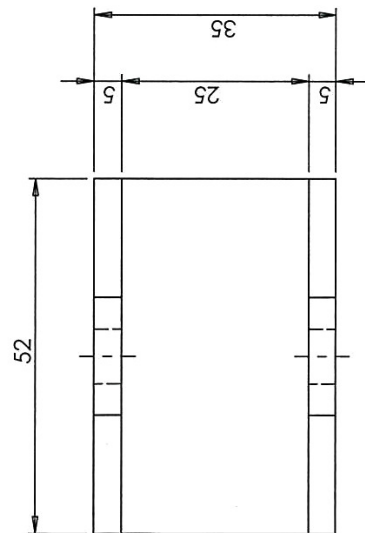
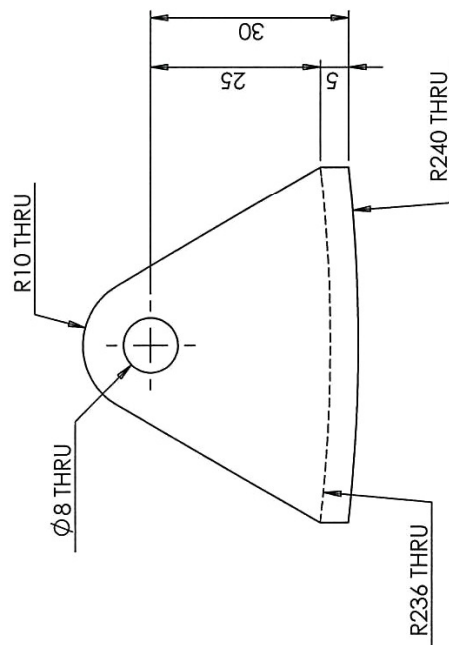
COUPLING [PP] $\phi 80$ L=110MM.
QTY 1 PCS.



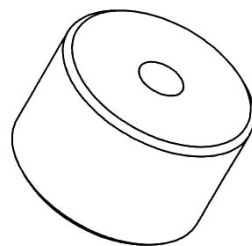
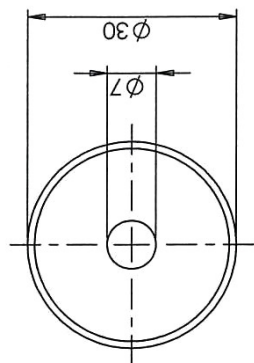
ภาพที่ 9
แบบวาดคัปปลิงขับถังหมุน



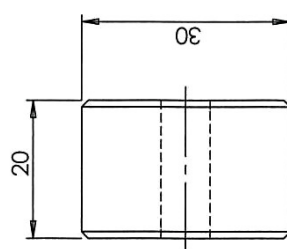
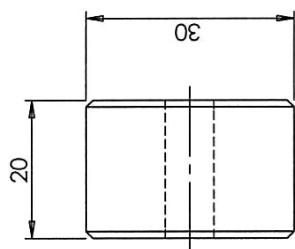
SUPPORT ROLLER
Q'TY 4 PCS.



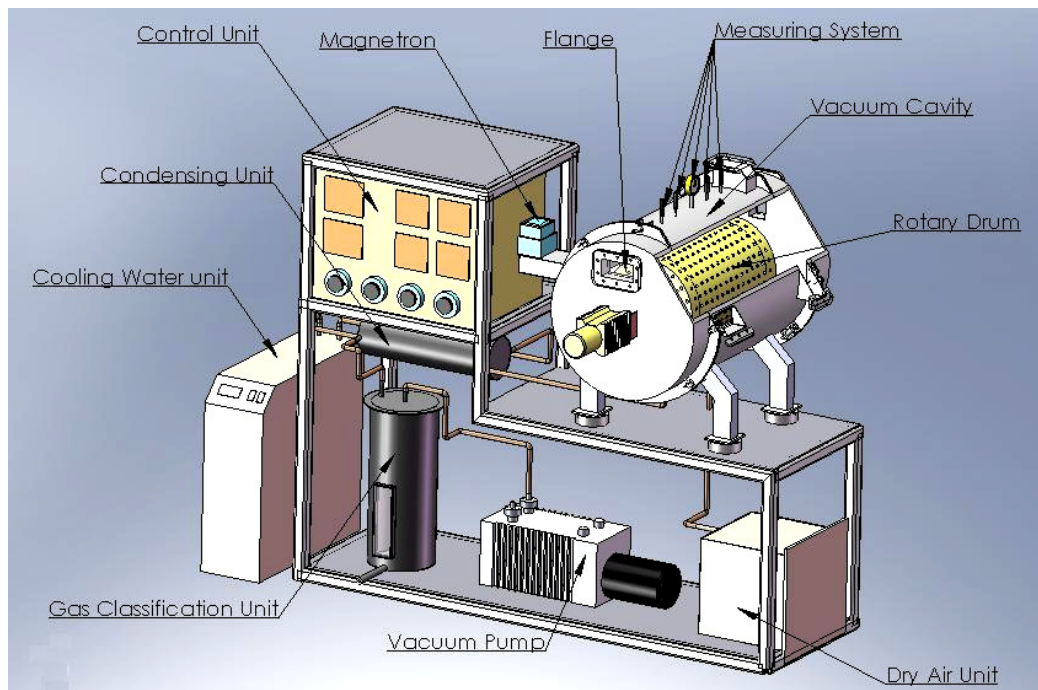
ภาพที่ 10
แบบวาดฐานล้อลูกกลิ้ง



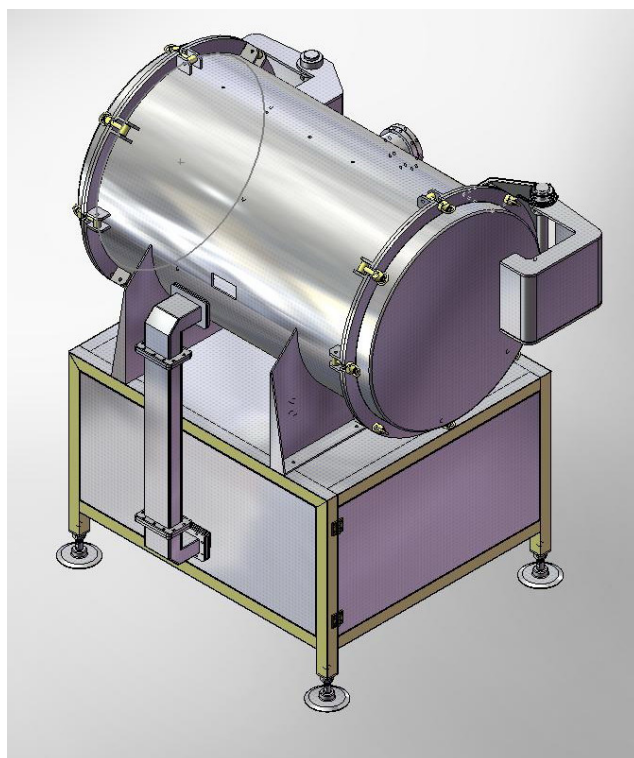
ROLLER [PP] Ø 30MM.
Q'TY 4 PCS.



ภาพที่ 11
แบบวาดล้อลูกกิ้ง



ภาพที่ 12 เครื่องอบแห้งเนกประสงค์เชิงพาณิชย์โดยใช้ไมโครเวฟร่วมกับระบบสุญญากาศ
(Multi-Feed Low Power Magnetron)



ภาพที่ 13 เครื่องอบแห้งเนกประสงค์เชิงพาณิชย์โดยใช้ไมโครเวฟร่วมกับระบบสุญญากาศ
(Single-Feed High Power Magnetron)

Manuscript Number:

Title: Design and analysis of the commercialized drier processing using a combined unsymmetrical double-feed microwave and vacuum system (case study: tea leaves)

Article Type: Full Text Article

Keywords: Microwave vacuum drying, Tea leaves, Heat and mass transfer, Quality

Corresponding Author: Phadungsak Rattanadecho,

Corresponding Author's Institution:

First Author: K. Jeni, Ph.D (candidate)

Order of Authors: K. Jeni, Ph.D (candidate); M. Yapa , Ph.D (candidate); Phadungsak Rattanadecho

Abstract: Combined microwave (MW) and vacuum drying of biomaterials has a promising potential for high-quality dehydrated products. A better knowledge of the drying kinetics of biomaterial products could improve the design and operation of efficient dehydration systems. The commercialized biomaterials drier using a combined unsymmetrical double-feed microwave and vacuum system was used for drying kinetics experiments with tea leaves. The system was operated in the vacuum range of 535 and 385 torr and MW power of 800 and 1600 W, respectively. In this study, the system can be operated either in continuous or intermittent modes in each experiments. Experiments show that in the case of high power level and continuous operating mode causes greater damage to the structure of tea leaves sample. Microwave drying at 385 torr ensured the shortest drying time and the best overall quality of dried tea leaves, and thus was chosen as the most appropriate technique for tea leaves drying.

Cover Sheet

Title : Design and analysis of the commercialized drier processing using a combined unsymmetrical double-feed microwave and vacuum system (case study: tea leaves)

Author: K.Jeni, M. Yapa and P. Rattanadecho*

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Thailand, Tel: 66-2564-3001-9,

Fax: 66-2564-3010, *E-mail: ratphadu@engr.tu.ac.th

Significant of this work:

The main objective of this research was to examine the feasibility of using MV-vacuum drier to dry biomaterials, i.e., tea leaves and experimentally explore drying characteristics of tea leaves in different MV conditions, including microwave radiation time, microwave power level, vacuum level and typical microwave feeding process. At the same time, the research results would be beneficial to present a theory

basis for further study and industrial application of MV technology in biomaterials in the future.

Design and Analysis of the Commercialized Drier Processing Using a Combined Unsymmetrical Double- Feed Microwave and Vacuum System (Case Study: Tea Leaves)

Kusturee Jeni, Mudtapha Yapa and Phadungsak Rattanadecho

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Mechanical Engineering

Faculty of Engineering, Thammasat University (Rangsit Campus), Pathumthani
12120, Thailand

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Abstract

Combined microwave (MW) and vacuum drying of biomaterials has a promising potential for high-quality dehydrated products. A better knowledge of the drying kinetics of biomaterial products could improve the design and operation of efficient dehydration systems. The commercialized biomaterials drier using a combined unsymmetrical double-feed microwave and vacuum system was used for drying kinetics experiments with tea leaves. The system was operated in the vacuum range of 535 and 385 torr and MW power of 800 and 1600 W, respectively. In this study, the system can be operated either in continuous or intermittent modes in each experiments. Experiments show that in the case of high power level and continuous operating mode causes greater damage to the structure of tea leaves sample. Microwave drying at 385 torr ensured the shortest drying time and the best overall quality of dried tea leaves, and thus was chosen as the most appropriate technique for tea leaves drying.

Keywords: Microwave vacuum drying, Tea leaves, Heat and mass transfer, Quality

1. Introduction

Nowadays, the most important thing in industries, except for producing the high quality products to the markets, is to increase productivity and to reduce production cost. In general, several production processes of agricultural and industrial products are related to drying either by a natural method or using energy from other sources resulting in a low production rate or a high cost products. Microwave drying is one of the most interesting methods for heating and drying materials [1]-[8].

Microwave-vacuum (MV) drying is a novel alternative method of drying, allowing to obtain products of acceptable quality. It permits a shorter drying time and a substantial improvement in the quality of dried materials, in relation to those dried with hot air and microwaves drying methods. Furthermore, other advantages including environmental friendliness at low temperature, which not only over-comes the limitation of low thermal conductivity of the material under vacuum due to the absence of drying medium, but also avoids the defect of internal crack and interior burning caused by excessive heating in microwave drying, and acquires a wide range of application on the pharmaceutical and food industries. Microwave-vacuum drying has been investigated as a potential method for obtaining high-quality dried foodstuffs, including fruits, vegetables and grains [9]-[16]. Drouzas et al. [17] applied the vacuum-microwave technique to investigate the process of model fruit gel drying. They studied drying kinetics under different levels of pressure and microwave power. Sunjka, Rennie, Beaudry, and Raghavan [18] dried cranberries using vacuum-microwave and microwave-hot air drying

1 techniques, and demonstrated better quality of the product obtained with
2 vacuum-microwave drying.
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4 An excellent review of the drying techniques in dielectric materials
5 using microwave energy has been presented by Mujumdar [19], Metaxas
6 and Meridith [20] and Schubert and Regier [21].
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8 Although combined MW-Vacuum drying has found some application
9 in the dehydration of fruit juices, more research and development is needed
10 before the process is used in large commercial scale. In particular, the effect
11 of vacuum and MW power on the drying kinetics should be known
12 quantitatively, so that the drying system can be optimized from the cost
13 and quality standpoints.
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15 The main objective of this research was to examine the feasibility of
16 using MV-vacuum drier to dry biomaterials, i.e., tea leaves and
17 experimentally explore drying characteristics of tea leaves in different MV
18 conditions, including microwave radiation time, microwave power level,
19 vacuum level and typical microwave feeding process. At the same time,
20 the research results would be beneficial to present a theory basis for
21 further study and industrial application of MV technology in biomaterials in
22 the future.
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24 **2. Design of unsymmetrical double-feed magnetrons in multi-mode cavity**

25 It is well known that the uneven field distribution creates the hot and
26 cold spots. Hot spot could contribute to the phenomena of runaway.
27 For food products, cold spots are unwelcome as they allow
28 bacteria to thrive if the temperature is not sufficient high enough
29 to kill them, which could cause food poisoning [22]. This reason
30 explains why a more uniform heating is generally desirable. In the
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1 past, many researchers have devised ways of improving the electric field
2 as well as heating distribution with varying the degrees of success by
3 changing either the source, the microwave feeding system, shape of
4 cavity or the environment surrounding the load. Some base their ideas on
5 empty cavities, which in a practical situation are meaningless [23, 24]. In
6 analysis, electromagnetic waves in the cavity were simulated to design
7 the microwave-vacuum system. The distributions of electric field strength
8 and mode generation were investigated in the simulation. COMSOL
9 software was used for constructing domain meshes while analysis and
10 Finite Element Method was used to solve the problems. Generated
11 modes inside the cavity were calculated by determining the number of
12 half- wavelengths in each of the principal directions. The quality factor
13 (Q-factor) and the maximum electric field strength E_{max} were calculated
14 by using the equations found in [20]. The time-average complex power
15 flow through a defined closed surface is calculated from Poynting's
16 theorem [4] when a microwave source is connected to the cavity.

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18 In this study, the idea of using the multiple sources is
19 presented. This idea is providing certain advantages such as lower
20 inventory of spare parts and less maintenance downtime, the method has
21 the added benefit of creating a good uniformity. However, when it comes
22 to improving the electric field as well as heating uniformity and low cross-
23 coupling using multiple feeds, the obvious question to ask is where and
24 how to position the feeds. The disadvantage with multiple feeds is the
25 mutual coupling that exists if they are improperly fed. The feed positioning
26 requires an understanding and knowledge of the electric and magnetic
27 field directions. As described above, the simulation is needed to determine
28 the positioning of feeds in cavity [24].

29 The principle behind the design of feed multimode cavities for
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1 improved heating and low cross-coupling can be demonstrated here in
2 various cases. With the details of calculations omitted, the simulation
3 results in various cases will be summarized in Fig. 1 with single-feed
4 cavity and double-feed cavity having different orientation, i.e. (symmetrical
5 double-feed and unsymmetrical double-feed magnetrons).
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11 Fig. 1(a) shows the simulation of electric field arrow plot of single-
12 feed wall on which the TE₁₀ waveguide is to be connected and microwave
13 power of 800 W is applied. It is observed that a single source and feed will
14 certainly create patchy regions of field maxima and minima. Fig. 1(b) and
15 (c) shows the simulation of electric field arrow plot in case of symmetrical
16 double-feeds magnetrons and unsymmetrical double-feeds magnetrons
17 on simultaneously, respectively, assuming that the double feeds provide
18 double the amount of power.
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28 The simulated result is that it is the excitation of similar modes in
29 symmetrical double-feeds magnetrons that increases the cross-coupling
30 which leads to uneven field distribution. The reason for high coupling
31 between feeds is because they are symmetrically positioned on the cavity
32 wall and therefore excite the same mode. The reduced this coupling is
33 done by using the unsymmetrical feeds placement where each port
34 excites a different set of modes. The conclusion drawn from these results
35 is that the electric field uniformity is better with double-feeds sources as
36 compared to one-feed source. Furthermore, a better energy spread
37 throughout the entire cavity is obtained with the unsymmetrical placed
38 sources with each one exciting discrete modes. This reason explains why
39 the concept designed by using unsymmetrical double-feed was performed
40 in this study. Although the empty cavity is off little practical applied, some
41 important conclusions can be drawn that are still valid for the loaded
42 cavity.
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1 The fabrication work on the microwave cavity, the cavity must be
2 closed and safe in terms of microwave leakage. To prevent wave
3 leakage, the countermeasure in double with a combination of
4 mechanical blocking filter and microwave absorber zone was fabricated
5 and used. Since the waves that leaked had a maximum frequency of
6 2450 MHz, the cutoff frequency of the wave-filter must be higher than
7 2450 MHz in order to prevent leakage.
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21 3. Materials and methods

22 3.1. Materials

23 The experimental materials comprised tea leaves from a farm
24 located North Part of Thailand, stored at 10°C until sample
25 preparation. Three hours before drying the bulk of tea leaves were
26 placed at ambient air temperature. The initial moisture content of
27 material was 172% (dry basis). All tea leaves used for drying were from
28 the same batch.
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40 3.2. Experimental program

41 An experimental stand for the commercialized biomaterials drier
42 using a combined unsymmetrical double-feeds microwave and vacuum
43 system was shown in Fig. 2(a). The microwave power was generated by
44 means of unsymmetrical double-feeds magnetrons according to design
45 concept as shown in section 2 (2 compressed air-cooled magnetrons of
46 800 W each for a maximum of 1.6 kW) operating at a frequency of 2450
47 MHz. The power setting could be adjusted individually in 800 W steps.
48 The microwave was conveyed through a series of rectangular (11.0 x
49 5.5 cm) wave guides to a metallic vacuum cavity of 0.13 m³ (¶ x 0.24² x
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0.72 m) in which the materials to be dried can be rotated by rotary drum in the cavity. The rotary drum was made of polypropylene with dimensions approximately of 30 cm radius and 50 cm length and the rotation speed of the rotary drum was controlled about 10 rpm in order to enhanced the interaction between microwave and dielectric load. The maximum vacuum degree was about 50 torr. The MW-vacuum drying experiments were carried out for two levels of microwave power (800 W and 1600 W) and two levels of vacuum pressure (385 torr and 535 torr). In this study, the system can be operated either in continuous or intermittent mode in each experiments.

The moisture content (dry basis) and dry matter content were measured according to the AOAC (1995) standards [25], using a laboratory scale system to an accuracy of 0.01 g. Optical fiber (LUXTRON Fluroptic Thermometer., model 790, accurate to $\pm 0.5^{\circ}\text{C}$) was employed for measuring the averaged temperature of bulk load in cavity. Optical fibers were used instead of conventional thermocouples because the latter absorb microwave energy and produce erroneous temperature indications. An infrared camera was used to control the temperature the cavity. A MultimeterTM Series Digital with PC interface was used to monitor the temperature inside the cavity and to facilitate feedback control of process.

An infrared camera was used to measure the surface temperature of the samples (accurate to $\pm 0.5^{\circ}\text{C}$). In MW-vacuum process, the leakage of microwaves was prevented by the countermeasure in double with a combination of mechanical blocking filter and microwave absorber zone filter to be provided each at the both covers end. The microwave leakage was controlled below the DHHS (US Department of Health and Human Services) standard of 5 mW/cm².

1 The dielectric properties for tea leaves samples were measured at
2 25°C using a portable dielectric measurement (Network Analyzer) over a
3 frequency band of 1.5 GHz to 2.6 GHz as shown in Fig. 2(b). The portable
4 dielectric measurement kit allows for measurements of the complex
5 permittivity over a wide range of solid, semi-solid, granular and liquid
6 materials. It performs all of the necessary control functions, treatment of the
7 microwave signals, calculation, data processing, and results representation.
8 The software controls the microwave reflectometer to measure the complex
9 reflection coefficient of the material under test (MUT). Then it detects the
10 cavity resonant frequency and quality factor and converts the information
11 into the complex permittivity of the MUT. Finally, the measurement results
12 are displayed in a variety of graphical formats, or saved to disk.
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28 **4. Results and discussion**

29 According to the electric field simulation of the drier cavity, a single
30 feed magnetron will certainly create patchy regions of field maxima and
31 minima. The using of multiple sources is presented to create a good
32 uniform electric field. The simulated result is that it is the excitation of
33 similar modes in symmetrical double-feeds magnetrons that increases the
34 cross-coupling which leads to uneven field distribution. The reason for
35 high coupling between feeds is because they are symmetrically positioned
36 on the cavity wall and therefore excite the same mode. The reduced this
37 coupling is done by using the unsymmetrical feeds placement where each
38 port excites a different set of modes. The conclusion drawn from these
39 results is that the electric field uniformity is better with double-feeds
40 sources as compared to one-feed source. Furthermore, a better energy
41 spread throughout the entire cavity is obtained with the unsymmetrical
42 placed sources with each one exciting discrete modes.
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1 The experiments were carried out on commercialized
2 biomaterials drier using a combined unsymmetrical double-feed
3 microwave and vacuum system. Three kilograms of tea leaves were
4 applied with the microwave power of 800 (single-feed magnetron) and
5 1,600 W (unsymmetrical double feed magnetrons) operating at 2,450
6 MHz frequency. Rotation rates of the rotary drum were held constant at
7 10 rpm. Vacuum Pressure was controlled at the constant pressure of
8 385 torr and 535 torr, respectively. In this study, the system can be
9 operated either in continuous or pulse mode in each experiments.
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11 Figs. 3 and 4 show the drying curves for tea leaves with
12 continuous and pulsed microwave operating modes. It is clearly evident
13 from these curves that the moisture content decreases continuously with
14 drying time. The drying rate was higher at lower pressure (stronger
15 vacuum degree), and the total drying time reduced substantially with the
16 decrease in pressure. In continuous microwave operating mode, the
17 drying times of tea leaves was 50 min in relation to the vacuum pressure
18 of 385 torr, and the drying times was 60 min for the vacuum pressure of
19 535 torr. As well as the continuous microwave operating mode with
20 power of 800 W the drying times was 60 min in relation to the vacuum
21 pressure of 385 torr and the drying times was 70 min for the vacuum
22 pressure of 535 torr.
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24 With pulsed microwave operating mode with of 1,600 W, the drying
25 times of tea leaves was 120 min in relation to the vacuum pressure of
26 385 torr and the drying times was 140 min for the vacuum pressure of
27 535 torr. For pulsed operating mode of 800 W, the drying time was 120
28 min in relation to the vacuum pressure of 385 torr and the drying time
29 was 140 min for the vacuum pressure of 535 torr. This is because water
30 with vacuum pressure of 385 torr has lower boiling point than water at
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vacuum pressure of 535 torr. Therefore, drying process at lower absolute pressure (stronger vacuum pressure) allows water to evaporate at a lower temperature. The drying curves show that the drying rate at lower absolute pressure (385 torr) is better than the drying rate at higher absolute pressure (535 torr) when microwave power is kept constant. Strong vacuum pressure leads to induce the faster of the drying rate. On the other hand, the drying rate also depends on the microwave power (Figs. 3-4). The continuous microwave operating mode with vacuum pressure of 385 torr has shorter drying time than continuous microwave operating mode with vacuum pressure of 535 torr by 16.7% for power of 1,600 W and 14.3% for power of 800 W, respectively. At lower vacuum pressure, drying time is shorter due to the reduced boiling temperature within the dried material. Along with the drying process, the moisture content of the tea leaves decreased. The latter arises from the fact that the microwave energy being absorbed decreased which leads to the drying rate decreased. It is due to the changing dielectric properties of the tea leaves which are proportionally dependent on moisture content.

It can be observed that magnetron control affects of drying curves of tea leaves. The drying times of continuous microwave operating mode are shorter than pulsed microwave operating mode. Hence, supplying microwave energy continuously gives less product quality. Figs. 9 and 10 show the physical appearance of tea leaves from continuous and pulsed microwave operating modes with power of 800 W in relation to the vacuum pressure of 535 torr. It is clearly evident from these figures that the pulsed microwave operating mode gives better physical appearance.

The averaged temperature of bulk load (i.e., tea leaves) is influenced by applied vacuum pressure and microwave power.

1 Magnetron power effects to internal heat generation and drying rate of
2 tea leaves. More microwave power input is induced the higher drying
3 rate and temperature (Fig. 5 to Fig. 8). Furthermore, the higher
4 microwave power increased the drying rate by providing more energy for
5 vaporizing water thus accelerating moisture removal at greater
6 temperature and more vacuum pressure allows water to evaporate at
7 lower temperature.
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9 The averaged temperatures of bulk load for the different drying
10 parameters are also summarized in Fig.5 to Fig.8 as a function of
11 elapsed times.
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13 The temperatures at power of 1,600 W, both of continuous and
14 pulsed operating mode in drying process, begin to reach a steady state
15 plateau at approximately 20 min after this stage the temperatures
16 increase slowly (Fig.5). The temperatures at power of 800 W reach a
17 steady state plateau at approximately 20 and 60 min with continuous
18 and pulsed microwave operating modes, respectively (Fig.6). The
19 averaged temperature being dried at the higher vacuum level (385 torr)
20 is lower than the temperature at lower vacuum levels (vacuum pressures
21 of 535 torr).
22

23 Fig. 5 shows the averaged temperature profiles for microwave
24 drying process with magnetron power of 1,600 W. For the continuous
25 microwave operating mode, the final average temperatures are reached
26 to 83°C and 85°C in the relation to the vacuum pressure of 385 torr and
27 535 torr, respectively. And for the pulsed microwave operating mode the
28 final averaged temperatures are reached to 64°C and 66°C in relation to
29 the vacuum pressure of 385 torr and 535 torr, respectively.
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31 Fig. 6 shows the averaged temperature profiles for microwave
32 drying process with magnetron power of 800 W. For the continuous
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microwave operating mode, the final average temperatures are reached to 77°C and 80°C in the relation to vacuum pressure of 385 torr and 80°C, respectively. And for the pulsed microwave operating mode, the final averaged temperatures are reached to of 64°C and 65°C in relation to the vacuum pressure at 385 torr and 535 torr, respectively.

Figs. 7 and 8 show the averaged temperature profiles for the pulsed microwave operating mode with magnetron power of 800 W and 1,600 W, respectively. It can be observed that no clearly difference in temperature distribution for two power levels was shown. However, for the continuous microwave operating mode, it has been found that the averaged final temperature for power of 1,600 W gives approximately 10°C higher than the averaged final temperature for power of 800 W.

Figs. 9 and 10 show the roughly color shades for tea leaves which were dried with pulsed and continuous microwave operating modes, respectively. It is observed that the drying with pulsed microwave operating mode gives better product quality in physical appearance.

It should be summarized again that the drying conditions at stronger vacuum pressure are increased the drying rate and decreased averaged temperature of bulk load. Drying at higher magnetron power are increased the drying rate and averaged temperature. Nevertheless, the drying in continuous microwave operating mode which causes energy losses and might damages the productivity. To alleviate this problem it was suggested to use pulse microwave operating mode when drying under higher microwave power. Hence it would be recommended to select the higher microwave power in pulsed microwave operating mode for successfully in drying.

As mentioned in the previous work, especially by the authors [5], indicated obviously that the energy consumption by using microwave

energy can save potentially more than the purely conventional drying. Nevertheless, in this primary study aimed on drying of biomaterials which has lack of essential factors for assessment the energy consumption and biomaterials, i.e., tea leaves has used in specific purpose in food or herb industries is produced in general purpose; therefore, estimate on energy consumption in biomaterials is suitable to perform.

5. Conclusion

Generally, in the conventional hot air drying process, the drying rate was fast in the beginning stage, but decreased sharply in the last stage. Rising of the hot air temperature could not enhance the drying rate in the last stage, but caused damages to the food quality. In the microwave-vacuum drying process, the drying rate increased with increase of microwave power and vacuum degree. Furthermore, experiments show that in the case of high power level and continuous microwave operating mode causes greater damage to the structure of tea leaves sample. The drying at 385 torr ensured the shortest drying time and the best overall quality of dried tea leaves, and thus was chosen as the most appropriate technique for tea leaves drying. Although combined microwave and vacuum drying has found some application in the drying of biomaterials more research and development is needed before the process is used in large commercial scale. In particular, the effect of microwave power-vacuum on the drying kinetics should be known quantitatively, so that optimization analysis is needed for this combined drying process to improve the final physical and chemical properties and products quality of the product further.

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References

- [1] K. G. Ayappa, H. T. Davis, E. A. Davis, J. Gordon, Analysis of microwave heating of materials with temperature dependent properties. *AIChE J.* 37 (3) (1991) 313-322.
- [2] P. Perre, W. Turner, Microwave drying of softwood in an oversized waveguide, *AIChE J.* 43 (10) (1997) 2579-2595.
- [3] P. Ratanadecho, K. Aoki, M. Akahori, Influence of irradiation time, particle sizes and initial moisture content during microwave drying of multi-layered capillary porous materials, *Heat Transfer, ASME J.* 124 (1) (2002) 151-161.
- [4] P. Ratanadecho, K. Aoki, M. Akahori, The characteristics of microwave melting of frozen packed bed using a rectangular wave guide, *IEEE Trans. Microwave Theory Tech.* 50 (6) (2002) 1487-1494.
- [5] P. Rattanadecho, N. Suwannapum, A. Watanasungsuit, A. Duangduen, Drying of dielectric materials using microwave-continuous belt furnace, *ASME J. Manuf. Sci. Eng.* 129 (1) (2007) 157-163.
- [6] P. Rattanadecho, N. Suwannapum, B. Chatveera, D. Atong, N. Makul, Development of compressive strength of cement paste under accelerated curing by using a continuous microwave belt drier, *Mater. Sci. Eng. A* 472 (2008) 299-307.
- [7] S. Curet, O. Rouaud, L. Boillereaux, Microwave tempering and heating in a single-mode cavity: numerical and experimental

investigations, Chem. Eng. Process.: Process Intensification 47 (9-10) (2008) 1656-1665.

[8] S. Vongpradubchai, P. Rattanadecho, The microwave processing of wood using a continuous microwave belt drier, Chem. Eng. Process.: Process Intensification 48(5) (2009) 997-1003.

[9] Z. W. Cui, S. Y. Xu, D.-W. Sun, Dehydration of garlic slices by combined microwave-vacuum and air drying, Drying Technol. 21 (7) (2003) 1173-1185.

[10] Z. W. Cui, S. Y. Xu, D.-W. Sun, Effect of microwave-vacuum drying on the carotenoids retention of carrot slices and chlorophyll retention of Chinese chive leaves, Drying Technol. 22 (3) (2004) 561-574.

[11] A. E. Drouzas, H. Schubert, Microwave application in vacuum drying of fruits, Journal of Food Engineering, 28 (1996) 203-209.

[12] W. Kaensup, S. Chutima, S. Wongwises, Experimental study on drying of chili in a combined microwave-vacuum-rotary drum dryer, Drying Technol. 20 (10) (2002) 2067-2079.

[13] T. M. Lin, T. D. Durance, C. H. Scaman, Physical and sensory properties of vacuum microwave dehydrated shrimp, Journal of Aquatic Food Product Technology 8 (4) (1999) 41-53.

[14] J. I. Wadsworth, L. Velupillai, L. R. Verma, Microwave-vacuum drying of parboiled rice, Transactions of the ASAE. 33 (1) (1990) 199-210.

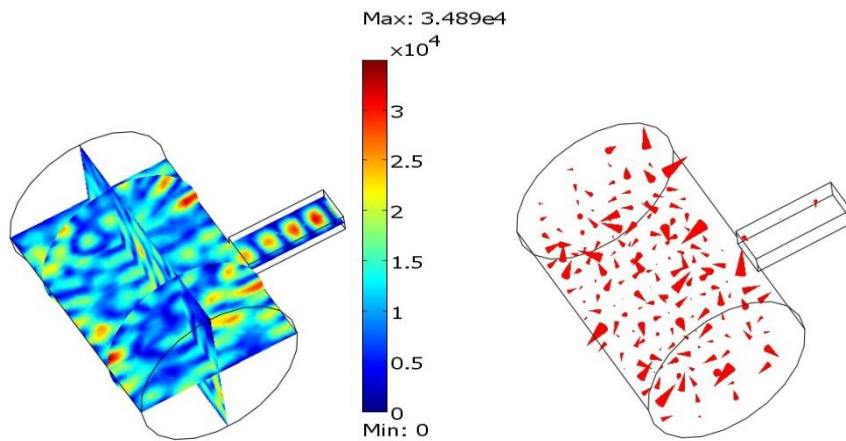
[15] J. Yongsawatdigul, S. Gunasekaran, Pulsed microwave-vacuum drying of cranberries, part I. Energy use and efficiency, Journal of Food Processing and Preservation 20 (2) (1996a) 121-143.

[16] Yongsawatdigul, J., & Gunasekaran, S. (1996b). Pulsed microwave-vacuum drying of cranberries, part II. Quality evaluation.

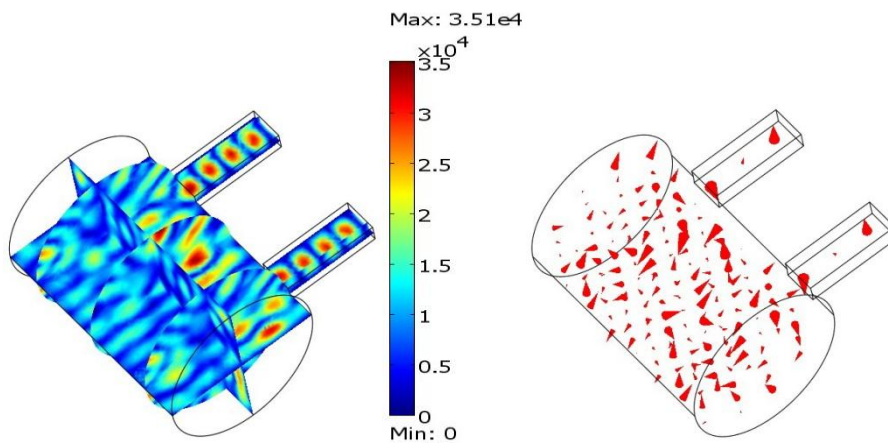
Journal of Food Processing and Preservation, 20(3), 145-156.

- [17] A. E. Drouzas, E. Tsami, G. D. Saravacos, Microwave-vacuum drying of model fruit gels. Journal of Food Engineering 39 (3) (1999) 117-122.
- [18] P. S. Sunjka, T. J. Rennie, C. Beaudry, G. S. V. Raghavan, Microwave-convective and microwave-vacuum drying of cranberries: A comparative study, Drying Technol. 22 (5) (2004) 1217-1231.
- [19] A.S. Mujumdar, Handbook of Industrial Drying, 2nd ed., Marcel Dekker, New York, 1995.
- [20] A.C. Metaxas, R.J. Meridith, Industrial Microwave Heating, Peter Peregrinus, Ltd., London, 1983.
- [21] H. Schubert, M. Regier, The Microwave Processing of Foods, Woodhead Publishing Limited and CRC Press, Cambridge, 2005.
- [22] R. V. Decareau, Microwave in the food processing industry, New York: Academic Press., 1985.
- [23] P. O. Risman, T. Ohlsson, B. Wass, Principles and models of power density distribution in microwave oven loads. J. Microwave Power EE (1987) 193-198.
- [24] T.V. Chow Ting Chan, H.C. Reader, Understanding Microwave Heating Cavities, Artech House, Inc, 2000.
- [25] AOAC, Official methods of analysis of AOAC international (16th ed.), USA, 1995.

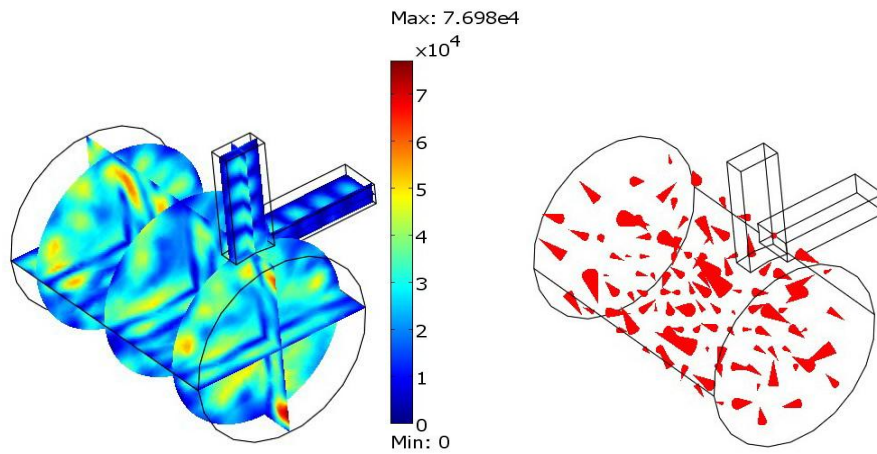
Figures



(a) Simulated electric field distribution and arrow plot in multimode cavity with one-feed single magnetron

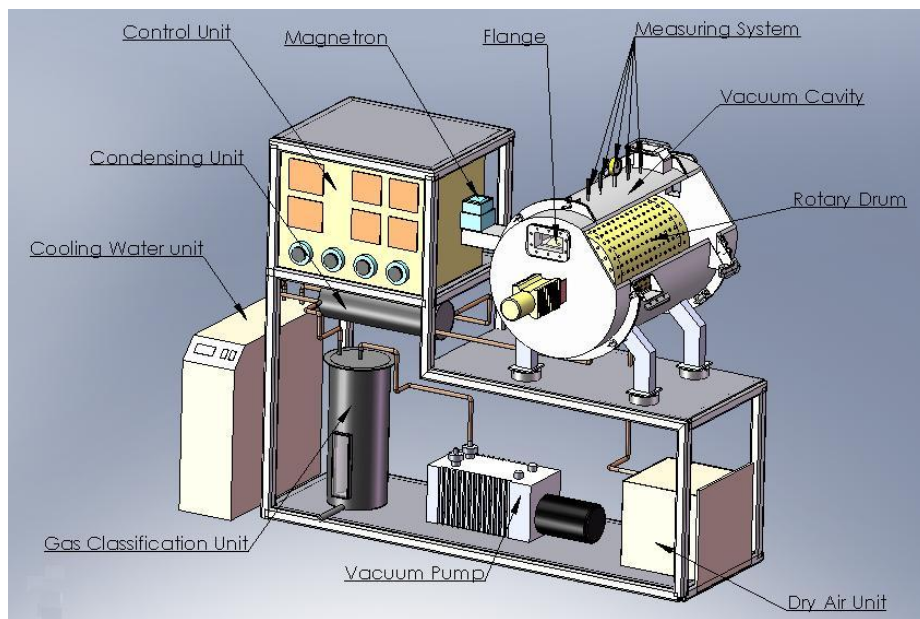


(b) Simulated electric field distribution and arrow plot in multimode cavity with symmetrical double-feed two magnetrons



(c) Simulated electric field distribution and arrow plot in multimode cavity with unsymmetrical double-feed two magnetrons

Fig. 1. The simulation of electric filed distribution (V/m) in multimode cavity (Slice Plot Type, and Arrow Plot Type)



(a)



(b)

Fig. 2. The commercialized biomaterials drier

(a) Detail of the system

(b) MW drying experiments were carried out at the Research Center of Microwave Utilization in Engineering (R.C.M.E.) Department of mechanical engineering faculty of engineering Thammasat university.

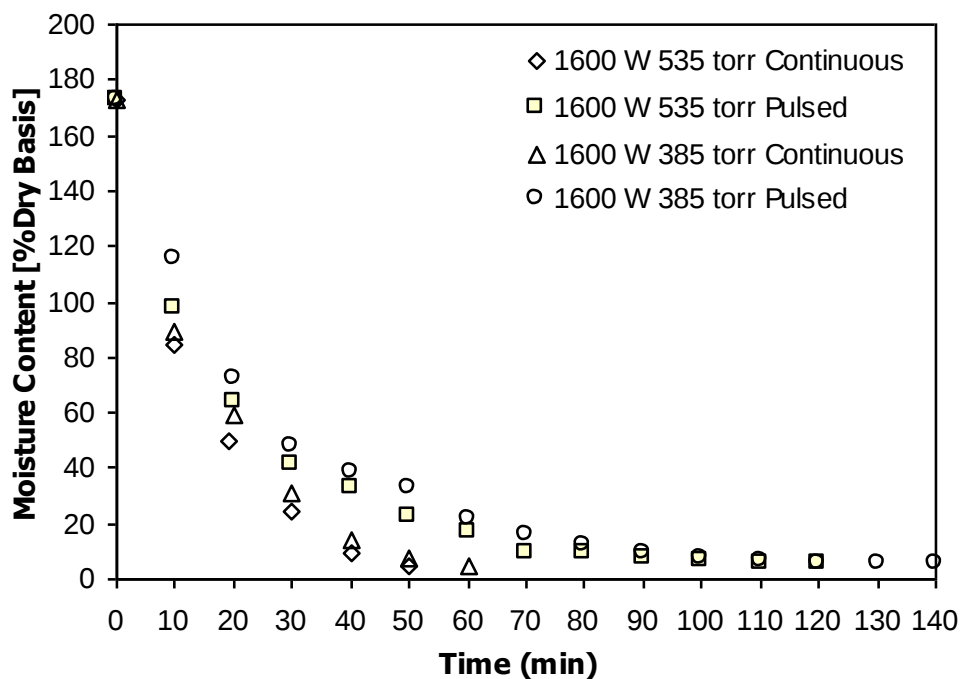


Fig. 3. Variations of moisture content with drying time of continuous and pulsed microwave distribution at 1,600 W magnetron power.

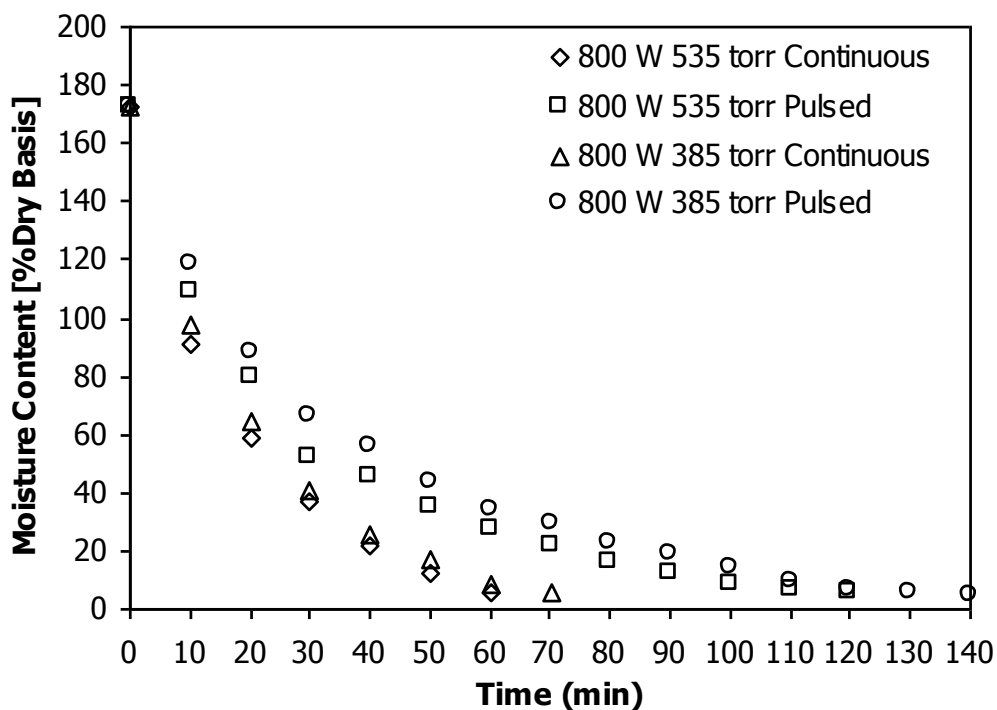


Fig. 4. Variations of moisture content with drying time of continuous and pulsed microwave distribution at 800 W magnetron power.

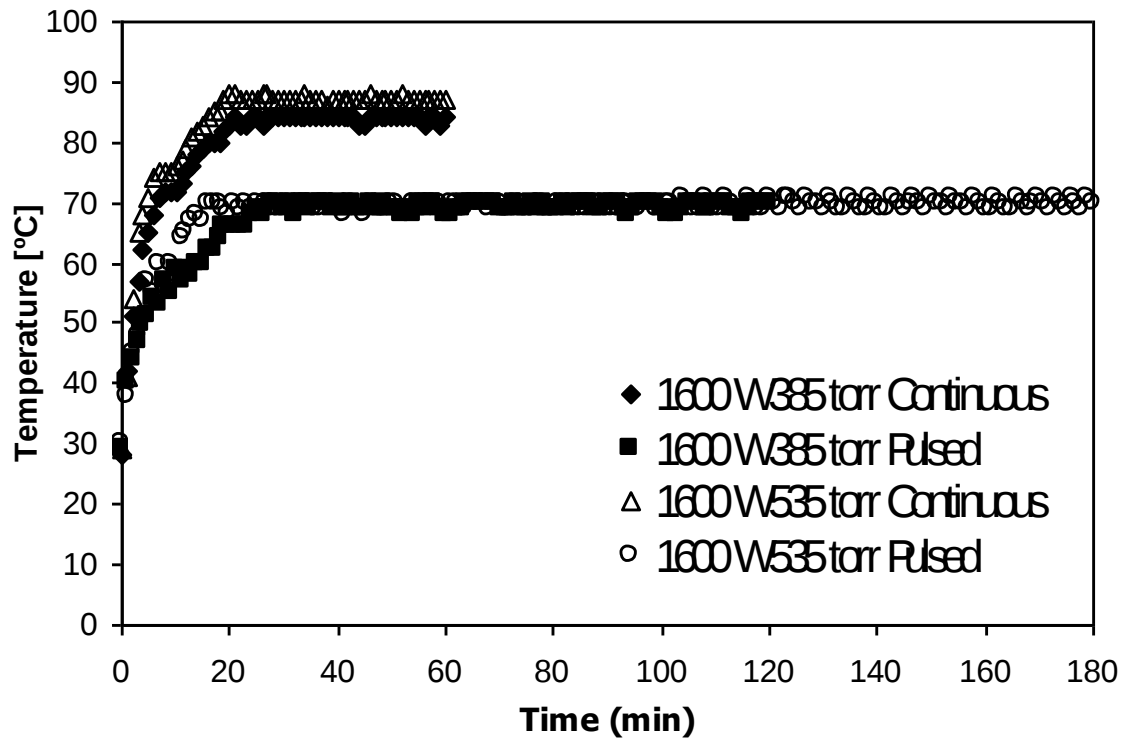


Fig. 5. Variations of cavity temperature with drying time of continuous and pulsed microwave distribution at 1,600W magnetron power.

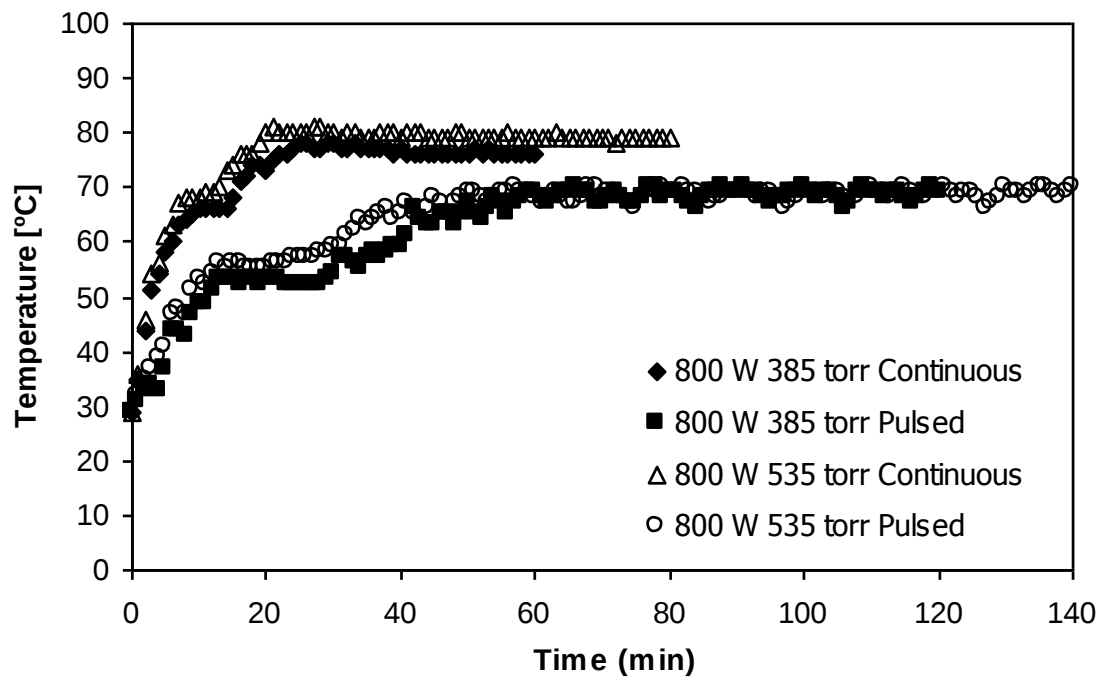


Fig. 6. Variations of cavity temperature with drying time of continuous and pulsed microwave distribution at 800 W magnetron power.

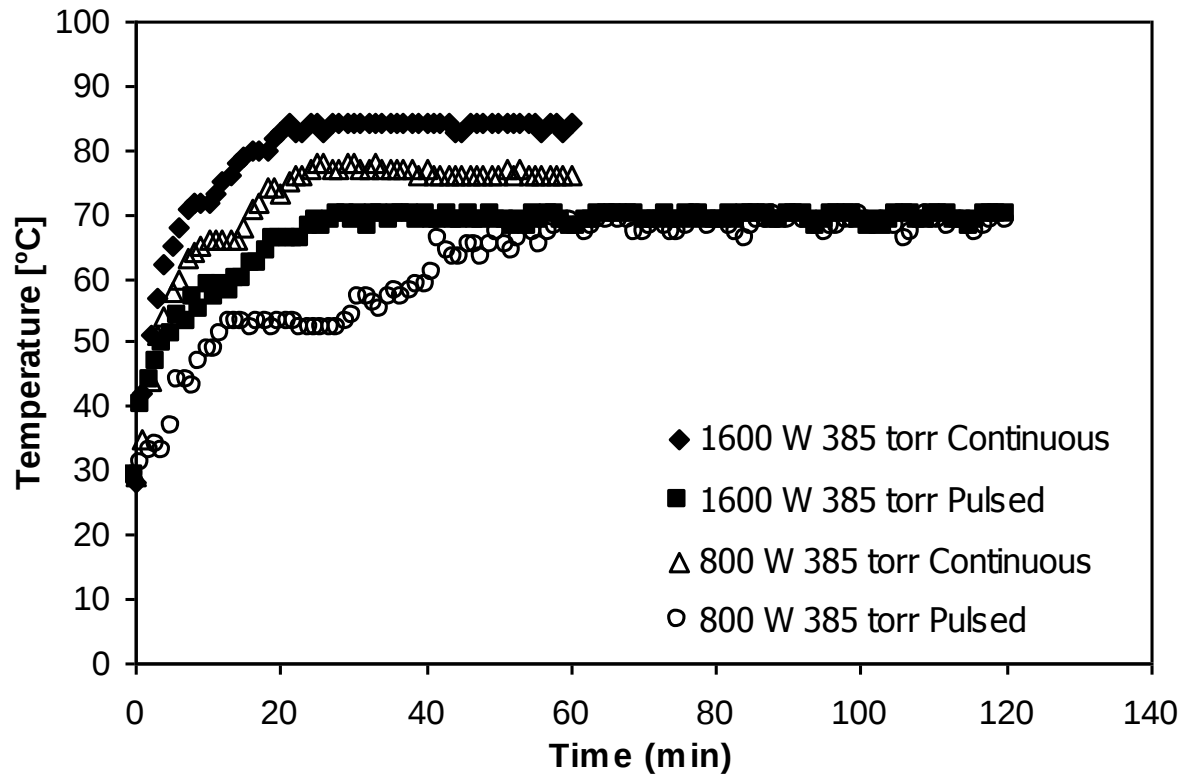


Fig. 7. Variations of cavity temperature with drying time of continuous and pulsed microwave distribution at 385 torr vacuum pressure.

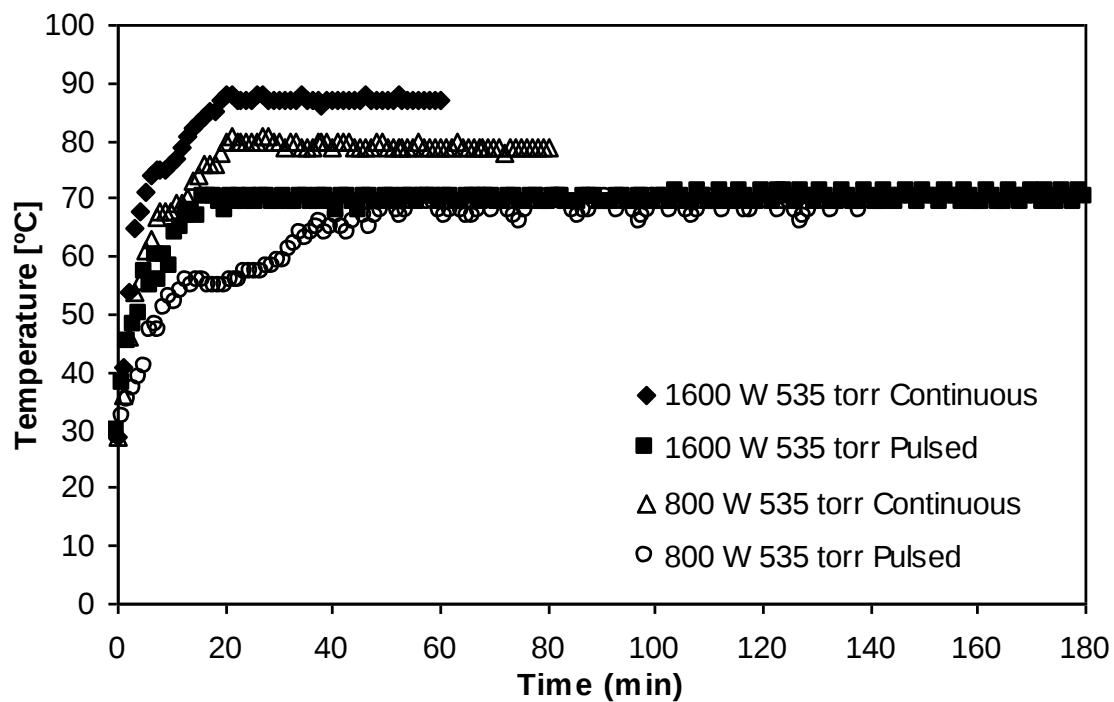


Fig. 8. Variations of cavity temperature with drying time of continuous and pulsed microwave distribution at 535 torr vacuum pressure.



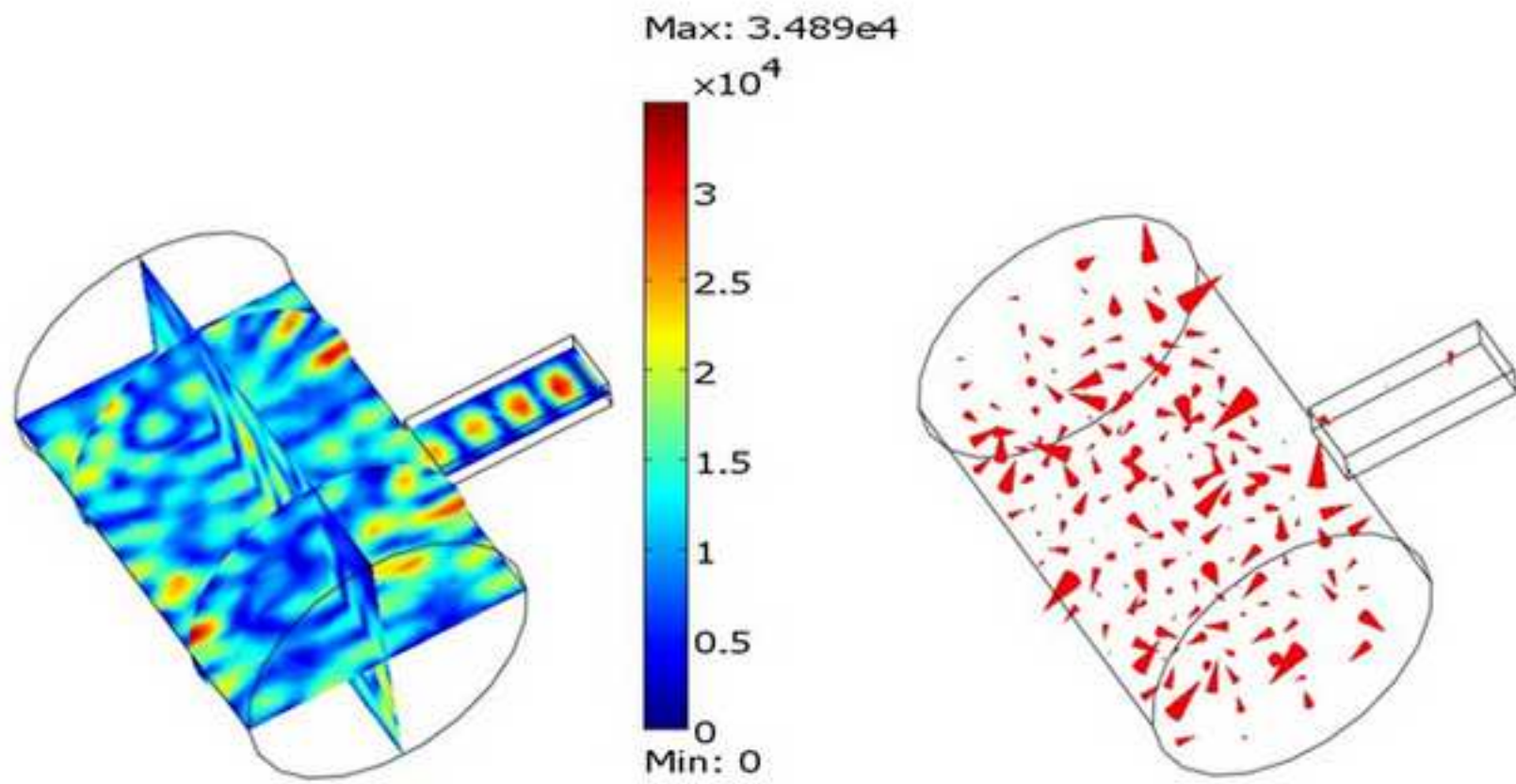
Fig. 9. Tea leaves with pulsed magnetron power



Fig. 10. Tea leaves with continuous magnetron power

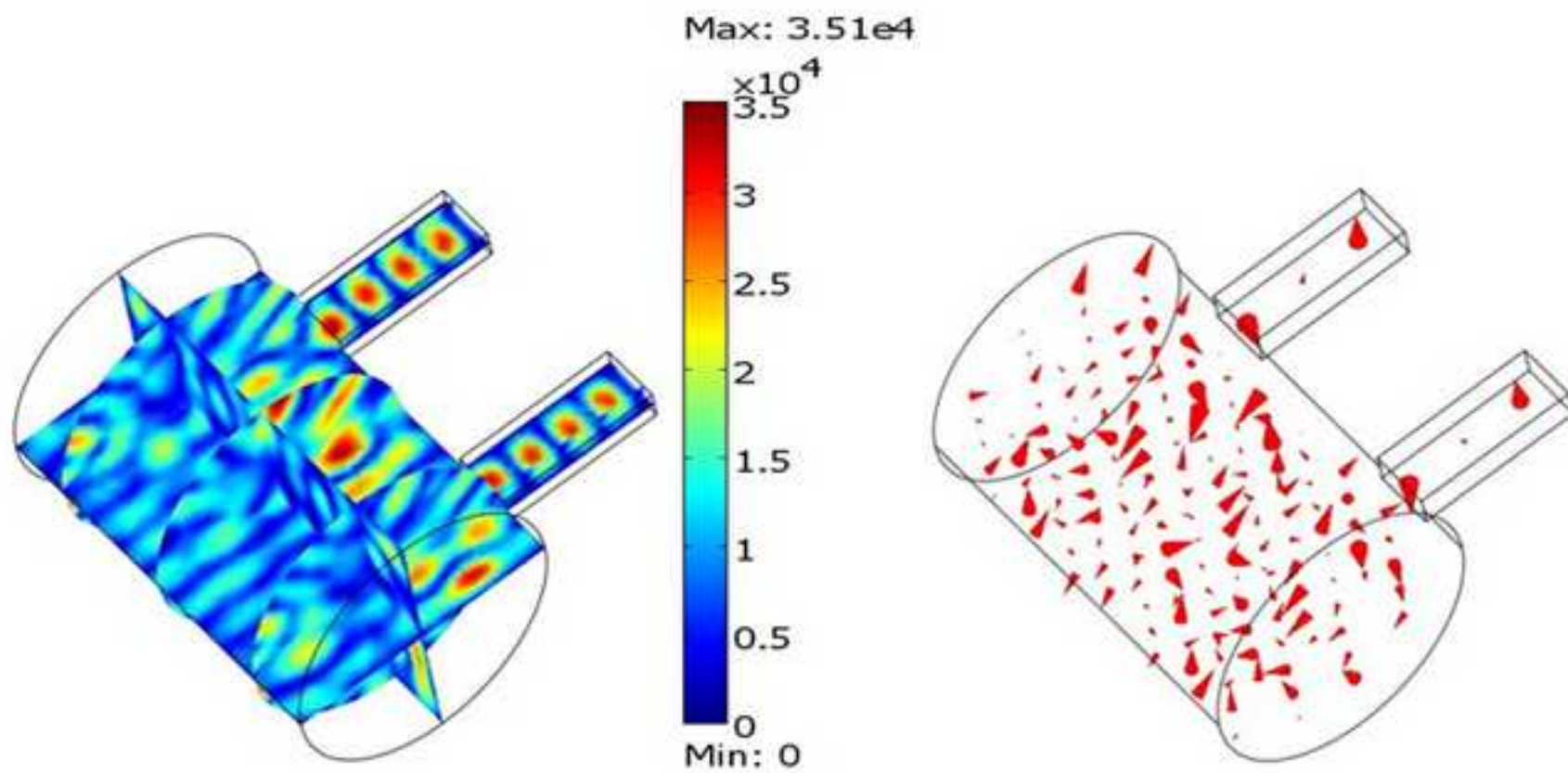
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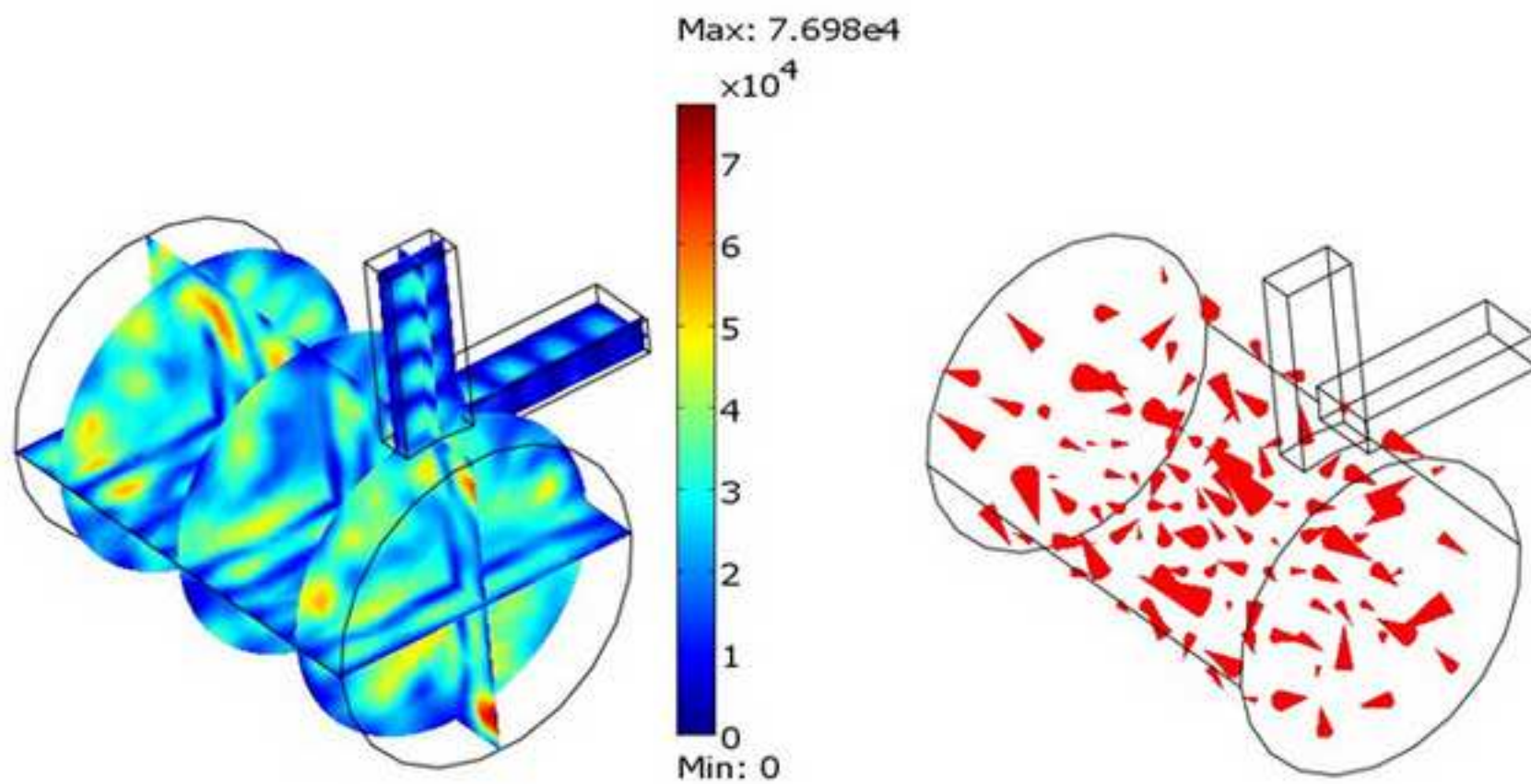
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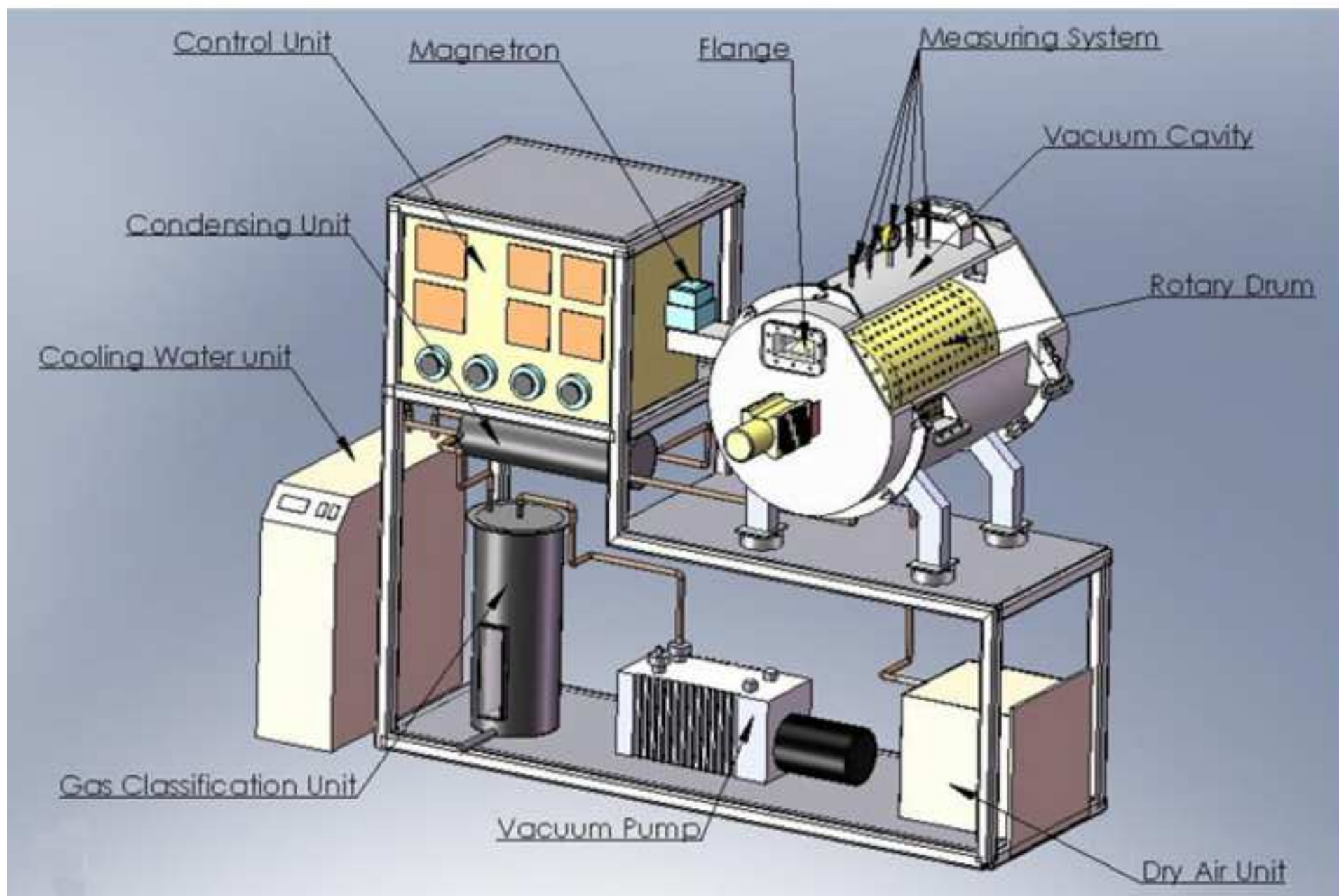
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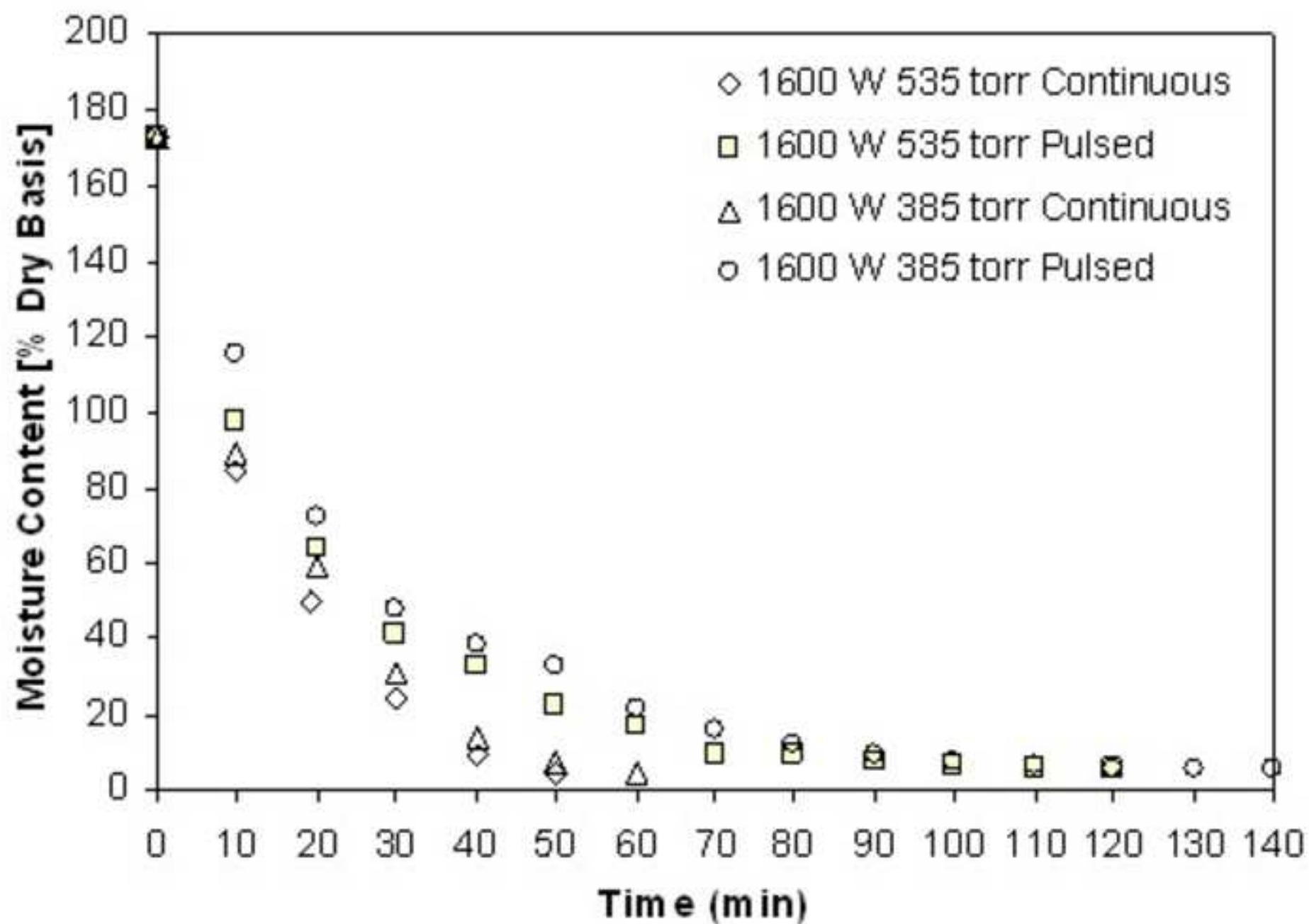


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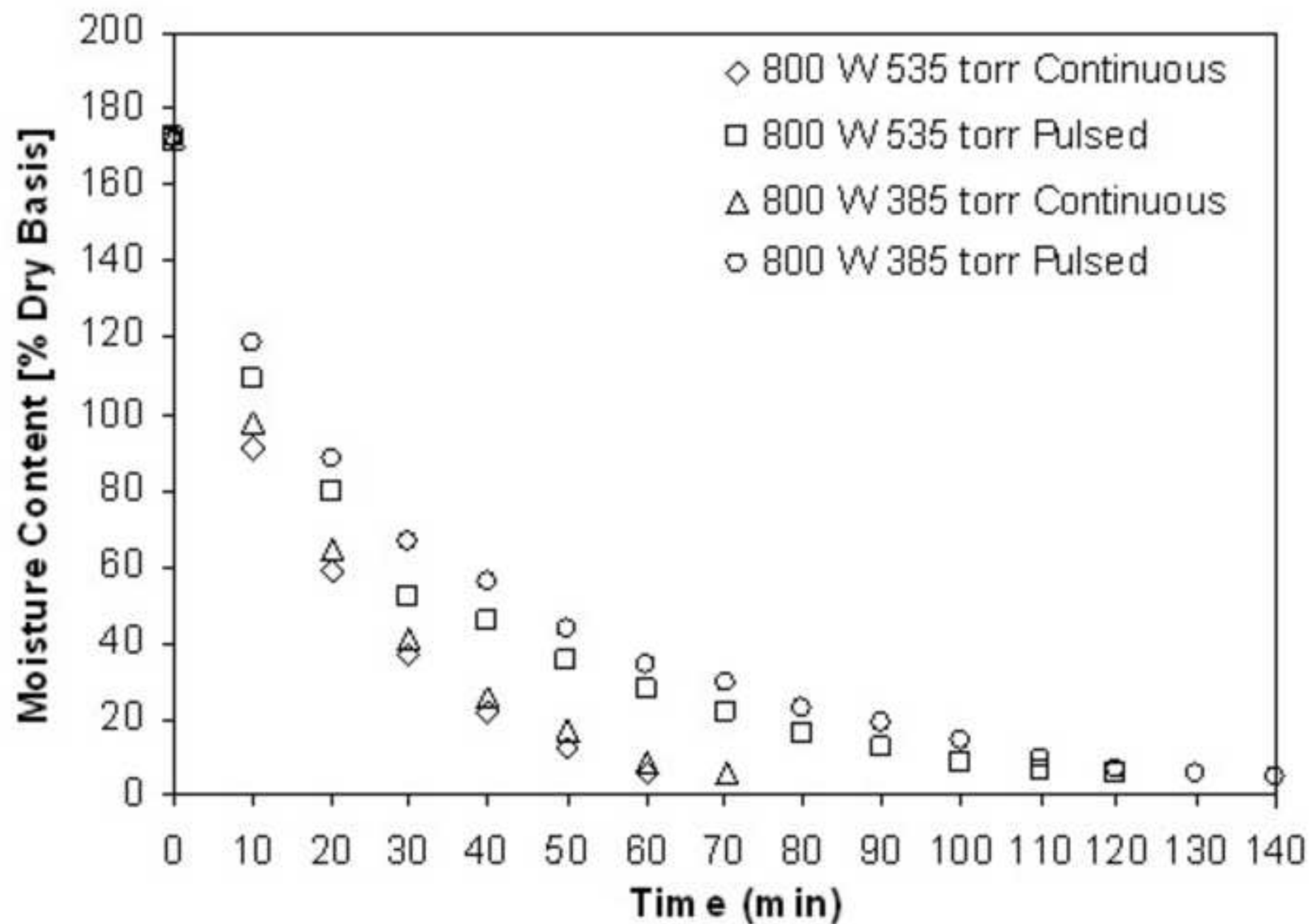


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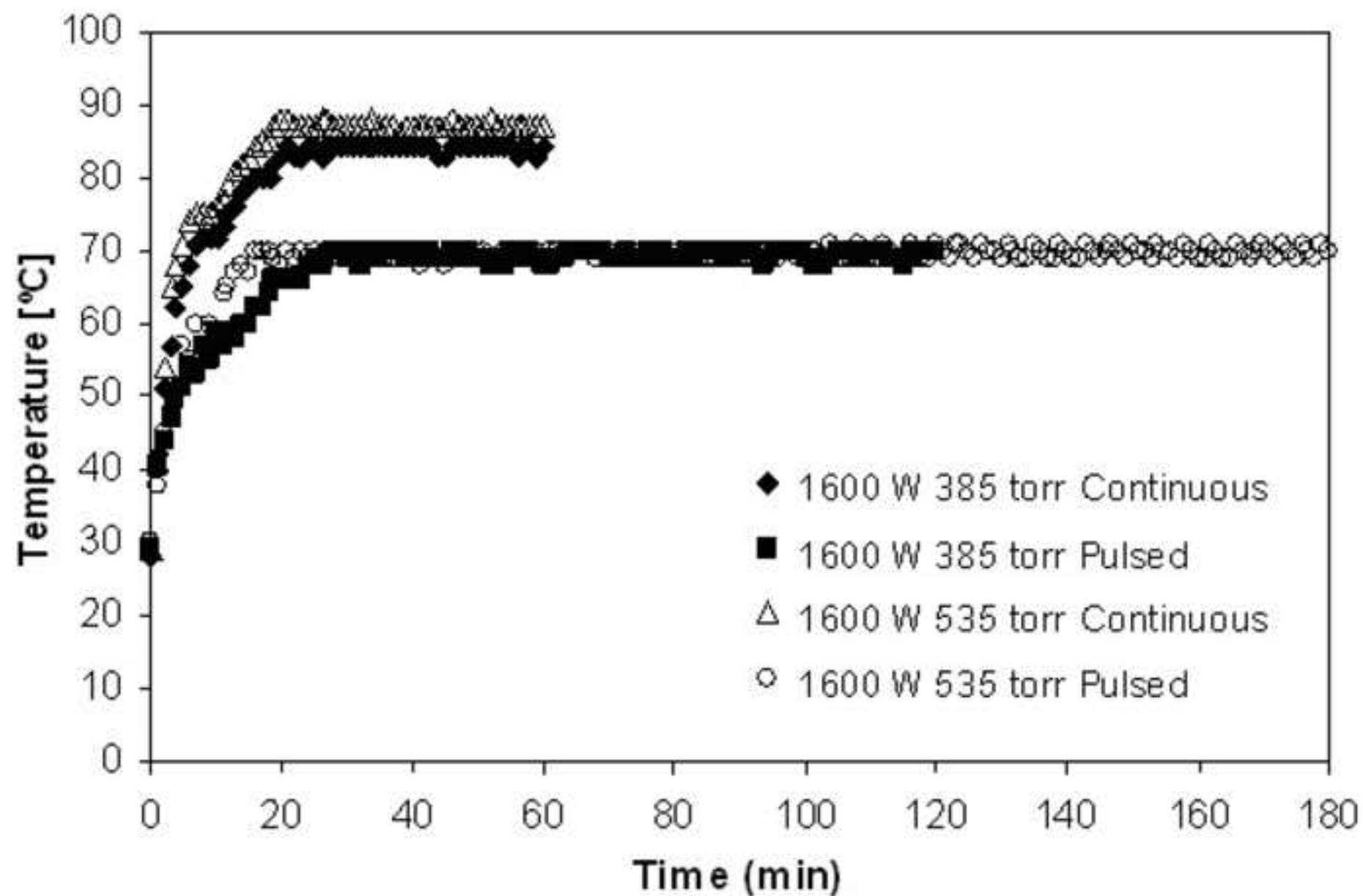


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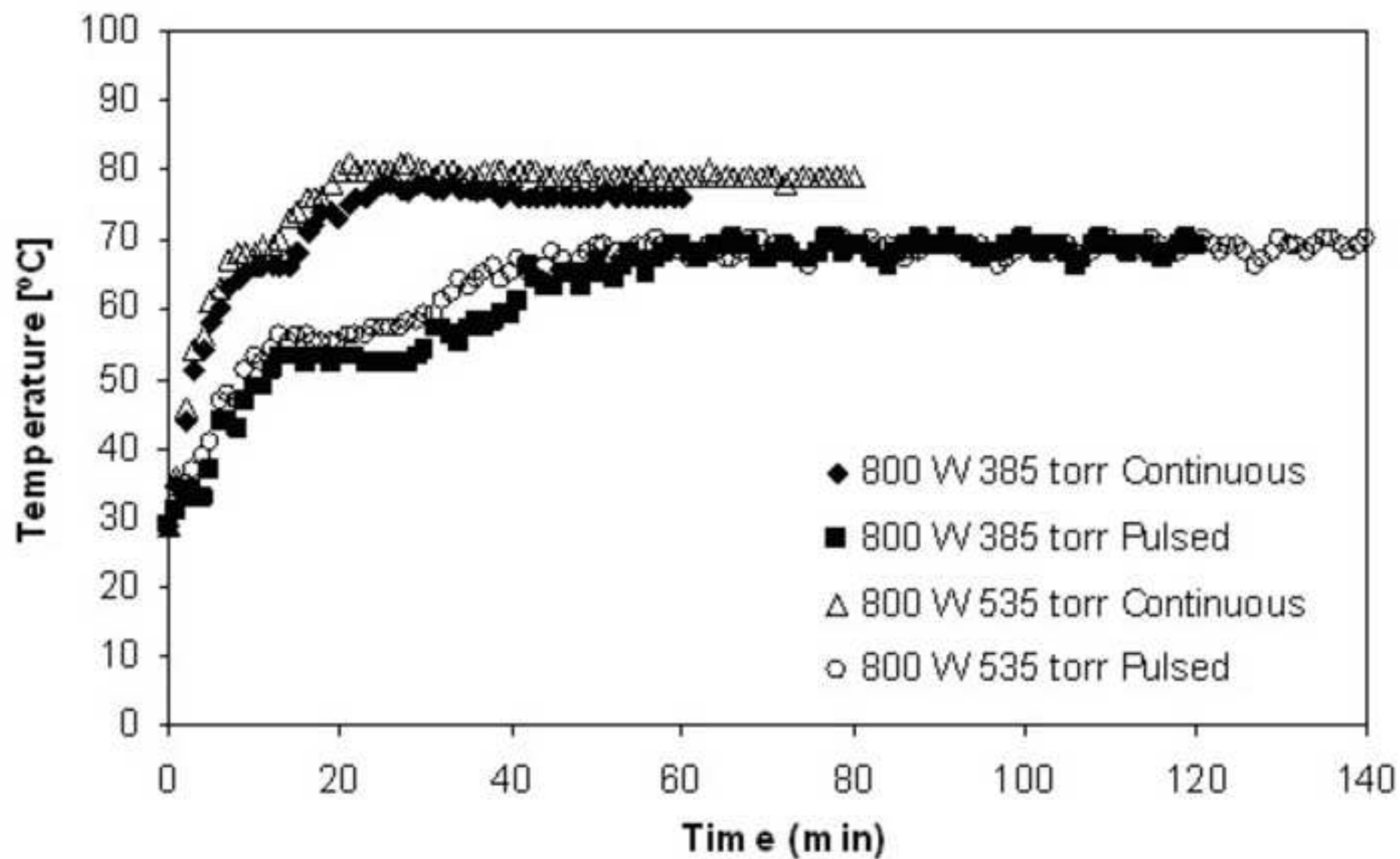
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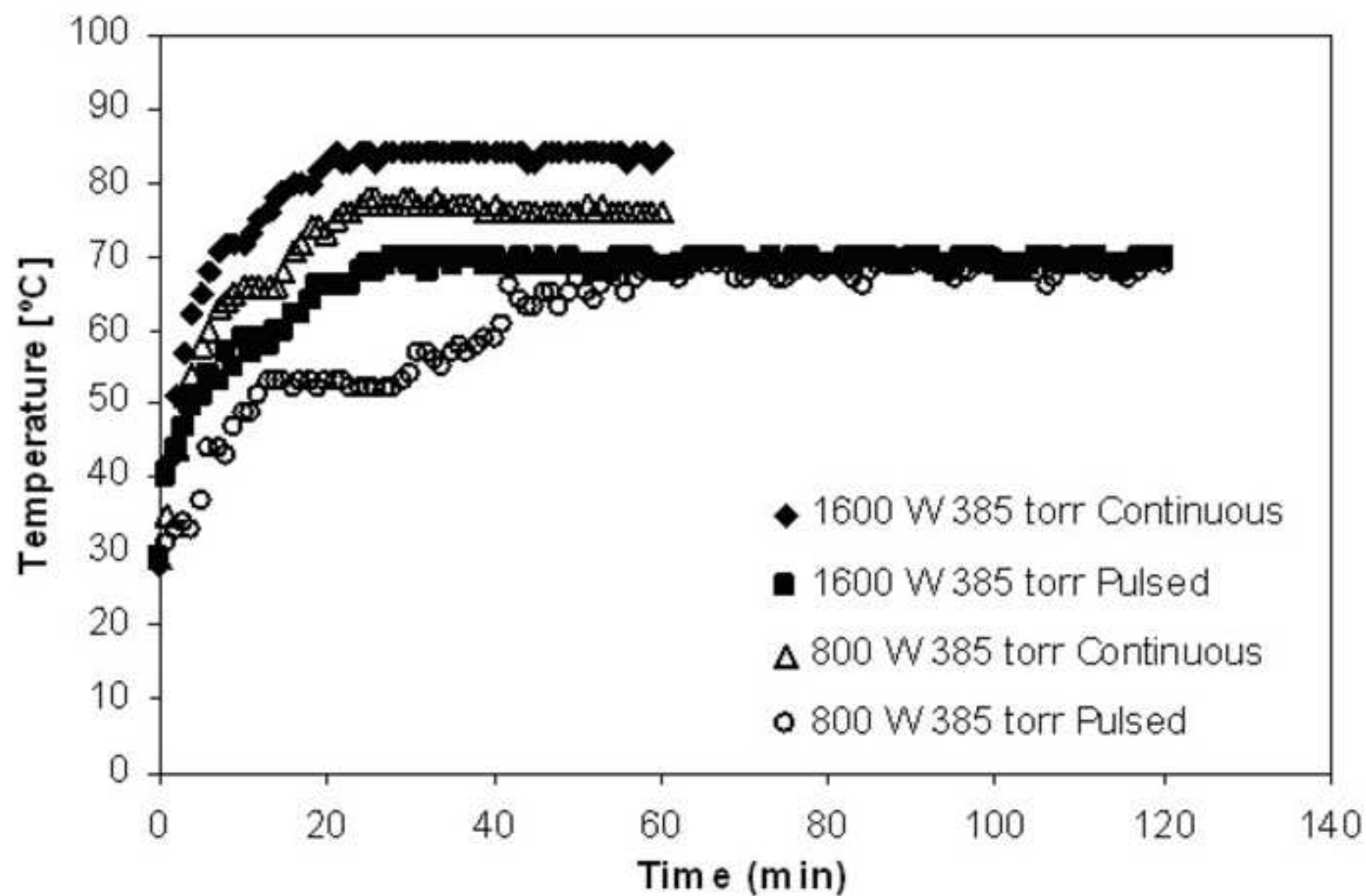
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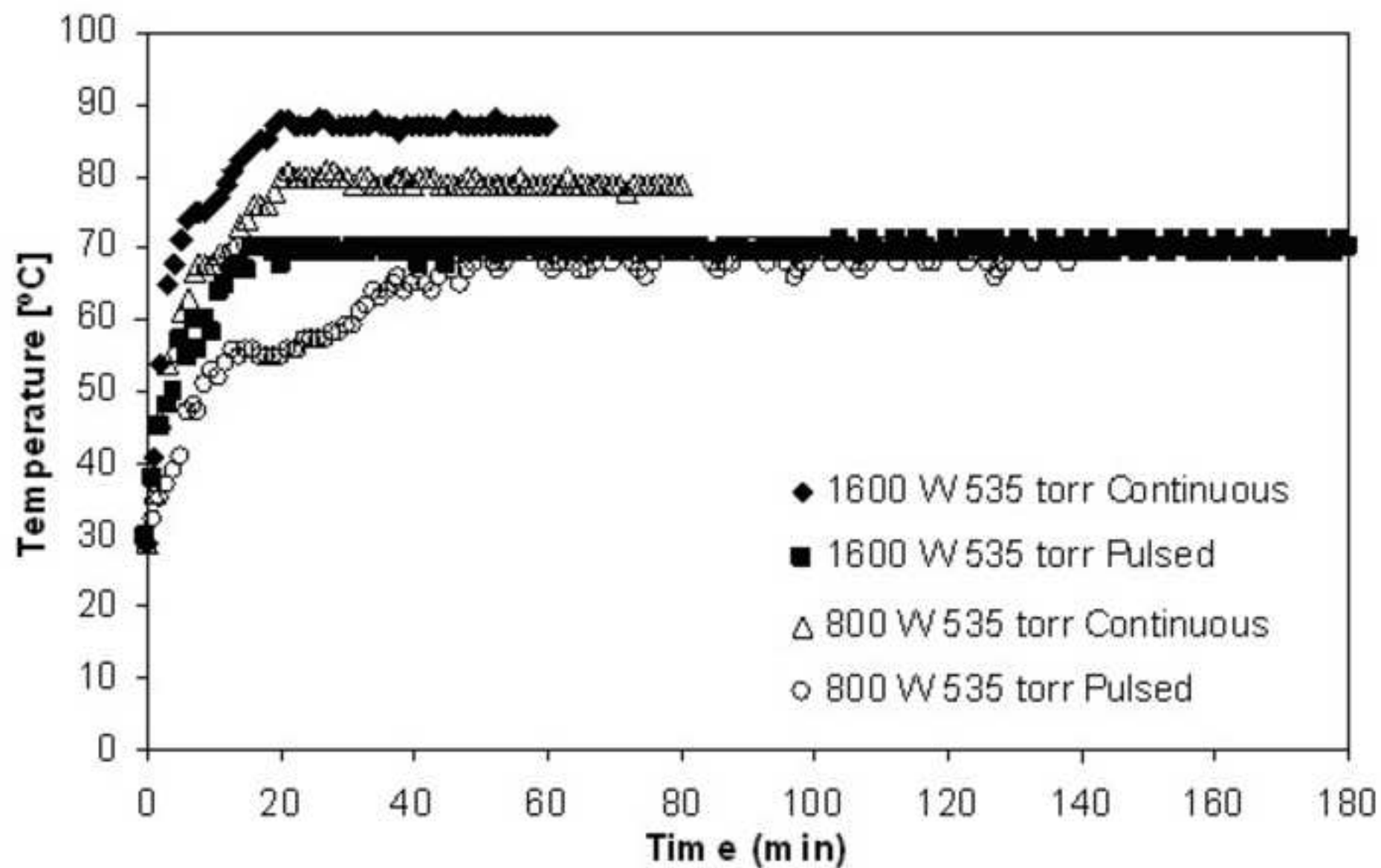
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