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Computational Fluid Dynamics Analysis of Stove Systems for Cooking and Drying of Muga Silk

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Abstract

In India, Silk industry plays an important part in textile industry. Muga silk, the golden yellow silk is quite unique to Assam, North-east India where its production is regarded as an important tool for economic development. But, outdated manufacturing technology is followed during the silk production in Assam. The existing cooking process of silk cocoons consists of boiling of silk cocoons in a stainless steel vessel along with water and soda in an open fireplace which is highly energy inefficient. Therefore, two modified systems have been designed; one having cylindrical boiling chamber (vessel) and the other having spherical boiling chamber (vessel). Both the chambers are having a cocoon heating chamber associated with them for cooking and drying of silk cocoons simultaneously. These designs are further classified into two types of designs based on channel and nozzle type combustion chambers. Therefore, the main objective of this paper is to improve the existing designs to maximize the utilization of heat carried by the combustion gases. These modified systems are analysed by using Computational Fluid Dynamics (CFD) selecting standard k–ϵ model. From the analysis, it is seen that these new systems having nozzle type combustion chambers are more efficient than the systems having cylindrical combustion chambers and if these systems are used in silk production, it will be very beneficial for the silk industry as well as for our society.

Keywords:

Muga Silk;
Boiling Chamber;
Cocoon Heating Chamber;
CFD Analysis.

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1- Introduction

Silk industry is having an exclusive position in India which plays a substantial role in textile industry and export. Geographically, Asia is the main producer of silk in the world and manufactures over 95% of the total global output. India is the 2nd largest producer of silk in the world and also the largest consumer of silk in the world and contributes 15% of the total world raw silk production. All the 4 commercially known varieties of silk, namely, Mulberry, Tasar, Eri and Muga are cultivated in India. India is the second largest producer of raw silk after China and the biggest consumer of raw silk and silk fabrics. Among these four varieties, Muga silk is known for its glossy fine texture and durability. This golden yellow silk is quite unique to Assam, a north-eastern state of India. Assam has the monopoly in the world in production of Muga, the "Golden Silk" as about 99% of Muga Silk is produced in Assam.

Silk is obtained from semi domesticated silk worm. The silk worm are raised outdoors primarily on host trees. The caterpillars are located on a tree and after stripping the tree of foliage, the caterpillars get out through the trunk. The keepers collect them and place them on a different tree. After getting ready to spin their cocoons, they again get out from the tree where feeding was going on. Due to such characteristics, the keepers can collect and control the caterpillars. After that, all caterpillars are put into a jail which is actually a container made of dried twigs. Due to the weakness of the peduncle i.e. the cocoon, the caterpillars favour a low place with several twigs so that those can be protected in their

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cocoons. The cocoons are collected after they matured. The maturity time varies on type of the variety of the silkworm. The cocoons are then dried in the sun and then dried in a hot air drying chamber till the cocoons lose 30-40% of its weight. The whole process takes about four hours. The cocoons are then cooked in a stainless steel vessel along with soda and water for 20 to 25 minutes. The temperature of the water is raised to around 90 to 95ºC. Then deflossing process takes place in which the gummy substance Sericin is removed. Then reeling process takes place which is followed by Lacing and Skeining. Lacing is done to separate the silk threads so that they do not adhere to each other. For Skeining, the laced hanks are to twist several times and fold the hank upon itself in a number of spirals. Then the silk thread is woven into fabric with the help of looms.

Sericulture and silk production have an enormous potential in India, but outdated manufacturing technology is being followed during the silk production as a result of which cost of silk production is high. For this silk industry, the energy availability scenario is also not very encouraging. This requires providing fresh technological input and evolving and establishing new systems for silk production. There are many areas in silk industry which is not explored by modern science n technology. Literature is also limited as there is not much research in this field. Few literatures having content with the theme of the present work were available which are systematically presented below.

Report on the Sericulture Manual [1] described the various processes that take place during the silk production. The method of silk production can be classified into mainly two processes, Pre cocoon technology and Post cocoon technology. Pre cocoon technology is concerned with cultivation of plants that silkworm feed on and rearing of silk worm. The Post cocoon technology is concerned with production of silk fibre from silk cocoons. The processes of the Post cocoon technology process are collection of suitable silk cocoons, stifling of cocoons (in case of Muga, Mulberry, and Eri silk), and sun drying, cooking of silk cocoons, lancing and skeining, reeling and re-reeling. The silk fibre is then woven into silk fabric with the help of handlooms and power looms. Baldwin (1986) [2] in his book showed the process to solve some technical problems of saving fuelwood supply. To modify the conventional energy technologies, he used the principles of modern engineering heat transfer and emphasized the importance of technical analysis to stove design, development, and dissemination. Bryden et al. [3] suggested some strategies which should be followed by a stove designer to improve a stove. It also highlights the synthesis of design created by Winiarski. In this report, Baldwin and Winiarski, gives the detailed information of combustion chambers with specification to support the designer in charge of developing a stove project.

Hadjisophocleous and McCartney (2005) [4] investigated the modeling of fire development and smoke production and provided a better understanding of fire dynamics concepts along with their limitations and impact on model predictions. Miltner et al. (2006) [5] studied CFD for the improvement and optimization of an innovative combustion chamber for a solid stem-shaped biofuel in the form of compressed biomass bales. Huttunen et al. (2004) [6] analysed a fuel bed model using CFD and obtained a consistent solution that satisfied both the equations of the bed and the flow model. The bed model provided the boundary conditions for the flow model owing to wood drying and pyrolysis. Prasad et al. (1981) [7] performed essential work on stove design and functioning where fire wood was used as fuel. Bhattacharya et al. (2002) [8] described twenty four different types of wood and charcoal burning stoves and measured emissions from those stoves. Bhattacharya et al. (2002) [9] also investigated the stove efficiency varying the pot size and concluded that the efficiency is independent of pot size of the stoves. Singh et al. (2018) [10] studied a boiling pot's feasibility with modified bottom surface and found that the pots with modified bottom having vertical tubes show 25-29% higher efficiency compared to the flat bottom pot. Nagaraju and Gopal (2018) [11] designed a heat recovery unit to improve the cooking cocoon process. Their study increased the oven efficiency, enhanced the comfort level of the workers and decreased the operational time. Gandigudea and Nagarhallib (2018) [12] studied the traditionally used inefficient three-stone fire cook stoves and improved the system based on the simulation results. They noticed desired performance for stove manufacturing with modified height. Pande et al. (2019) [13] studied the flaws in the traditional existing stoves in rural locations of Maharastra. Their modified stove model increased the thermal efficiency which was compared with traditionally used cook stoves through experimental analysis. Sedighia and Salarianb (2017) [14] noticed that geometric variables are having an effect on the efficiency and emissions of cooking stoves. They concluded that an optimum value for heating height is required to increase the cooking stove efficiency.

From the available literature, it has been observed that very less research work has been done related to design and analysis of stoves for silk production of Assam. Therefore, in this present study four different systems have been designed and simulated using CFD software, so that the cooking vessel can get higher temperature for drying the silk cocoons in the cocoon heating chamber.

- A system having cylindrical boiling chamber and channel type combustion chamber using CFD.
- A system having cylindrical boiling chamber and nozzle type combustion chamber using CFD.
- A system having spherical boiling chamber and channel type combustion chamber using CFD.
- A system having spherical boiling chamber and nozzle type combustion chamber using CFD.

2- Comparison between Two Types of Modified Systems Having Cylindrical and Spherical Boiling Chambers Using CFD

The existing cooking process of silk cocoons consists of boiling of the silk cocoons in a stainless steel vessel along with water and soda in an open fireplace. From the available energy analysis [15] it is known that the efficiency of cooking process of silk cocoons is 17.2% for Muga silk and 18.2% for Eri silk respectively. So, two modified systems are designed that are expected to be more energy efficient than the existing system.

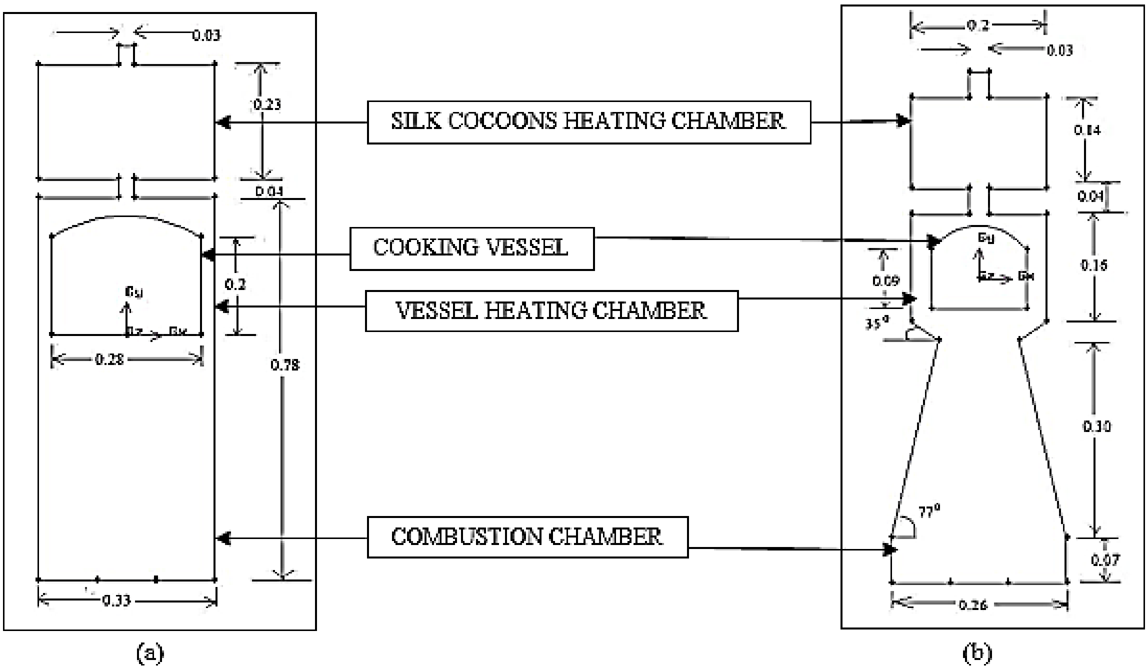

Figure 1. Schematic diagram of (a) system having cylindrical boiling chamber and channel type combustion chamber and (b) system having cylindrical boiling chamber and nozzle type combustion chamber.

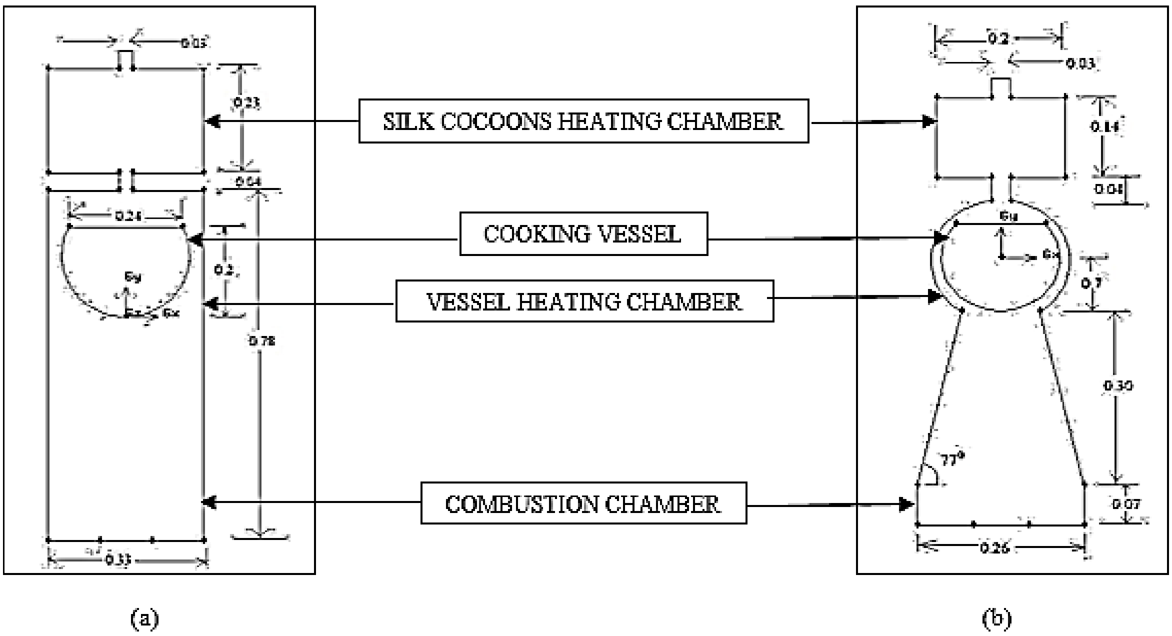

Figure 2. Schematic diagram of (a) system having spherical boiling chamber and channel type combustion chamber and (b) system having spherical chamber and nozzle type combustion chamber.

For each modified system, there is a furnace, a cooking vessel heating chamber and a silk cocoons heating chamber. In the cooking vessel heating chamber, silk cocoons are cooked in a cooking vessel whereas in the silk cocoons heating chamber, silk cocoons are dried by using hot combustion gases.

In the channel type combustion chamber, the hot gas is forced up through a narrow channel over the entire cooking vessel heating chamber so that the convective heat transfer is increased. The chamber is placed close to the fire to ensure good radiant heat transfer. Channel combustion chamber increases the pot (cooking vessel) area exposed to the hot gas by forcing the gas over as much of the surface of a single pot as practicable. Radiant transfer is maximized by placing the pot close to the fire bed without excessively interfering with the combustion. Channel combustion chamber of stoves offer high efficiencies, good control, and low cost. In the nozzle type combustion chamber, the gas is accelerated up the high and narrowing combustion chamber and then forced through a narrow channel over the cooking vessel heating chamber so that the convective heat transfer is increased. Emissions are reduced by bringing fresh air in at an angel to the combustion chamber, causing swirl and improving mixing of air with volatiles; by placing the baffle above the fuel bed to generate recirculation zones and thus improve combustion; and by providing a high combustion zone to allow completion of combustion. Nozzle combustion chamber of stoves has higher efficiencies than channel stoves. Further, because the shape of the combustion chamber which improves combustion, nozzle stoves have much lower emissions than other types. To maximize heat transfer to the cooking vessel, the hot combustion gases formed due to combustion of the fuel is passed through a narrow gap between cooking vessel and the chamber enclosing the cooking vessel. As the hot gases pass through the narrow gap, its velocity increases. The high velocity hot combustion gases heats up the cooking vessel faster due to friction between the cooking vessel and hot combustion gases. The combustion gases coming out from chamber enclosing the cooking vessel are then passed through another chamber called Cocoon heating chamber used for drying of the silk cocoons.

In the existing system, the heating process of the silk cocoons and cooking process are done separately where in the modified system both heating process and the cooking process of the silk cocoons can be done simultaneously. Even after cooking of silk cocoons, the hot combustion gases can be utilized for heating of the cocoons in the cocoon heating chamber. Thus, modification is done in such a way that most of the energy released by the fuel can be utilized which lowers the cost of silk production. On the basis of above concept, two modified system are designed, one having channel type combustion chamber and the other having nozzle type combustion chamber. The diagrams of these systems are shown in Figures 1 and 2 where all dimensions are in meters.

3- Methodology

For carrying out combustion of wood in FLUENT, discrete phase modeling (DPM) is used [16]. An injection system is created by selecting the discrete phase option with mass flow rate 0.5 kg/s. The modified system is modeled in the pre-processor Gambit 2.3.16 and then analyzed in Fluent 6.3.16. Steady and k–ϵ model is taken and for carrying out combustion, UDF file is created using injection system in fluent software [17].

In Figure 3 the mesh generation of the computational domains have been depicted for the four modified systems considered. In Figure 4 the results of the grid independence study have been shown.

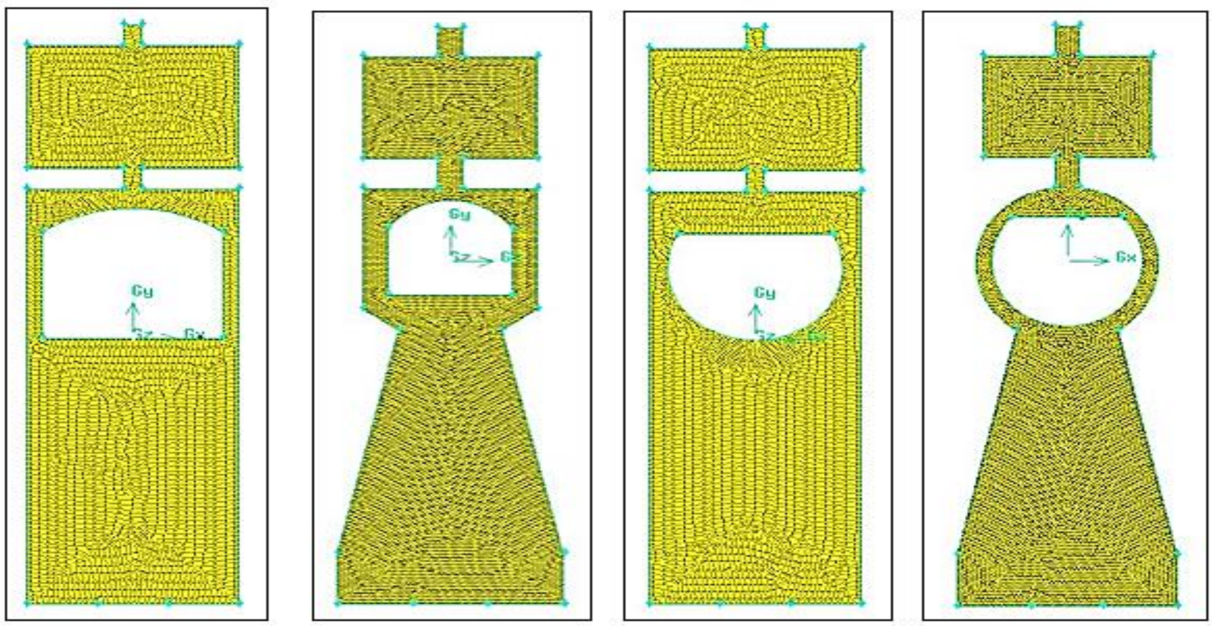

Figure 3. Mesh generation in the computational domain for the four different modified systems.

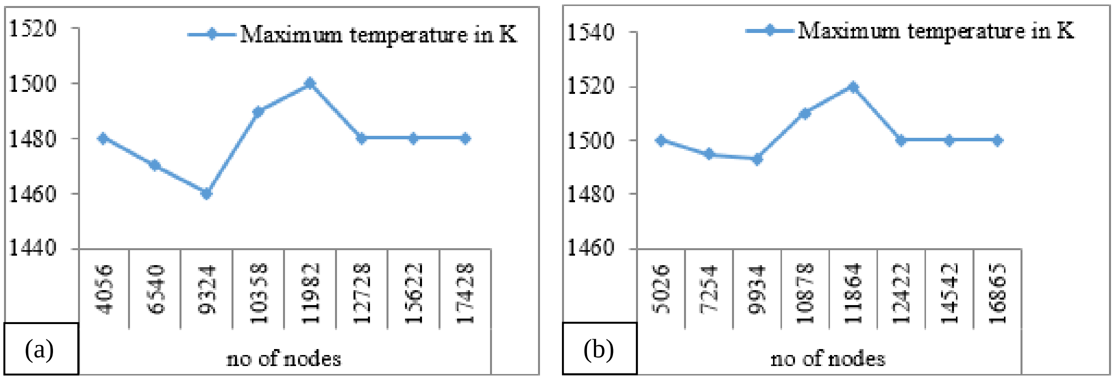

Figure 4. **Grid independence test for the modified systems having (a) channel type combustion chamber and (b) nozzle type combustion chamber.**

4- Results and Discussions

From Figures 5 (a) and (b), it can be noticed that in case of cylindrical boiling chamber, the modified system having nozzle type combustion chamber is having higher bottom wall temperature of 1070 K as compared to the same as 1060 K of the modified system having channel type combustion chamber wall for same amount of wood burnt. This means cooking vessel will get heated up faster in the modified system having nozzle type combustion chamber. Again, from Figures 5 (c) and (d) it is seen that for the spherical boiling chamber, the modified system having nozzle type combustion chamber has higher bottom wall temperature of 1080 K as compared to the same of 1070 K of the modified system having channel type combustion chamber wall. It is also witnessed that the modified system having nozzle type combustion chamber has higher side wall temperature of 696 K as compared to the side wall temperature of 636 K of the modified system having channel type combustion chamber wall for same amount of wood burnt. Again, the modified system having nozzle type combustion chamber is having higher side wall temperature of 704 K as compared to the same of 654 K of the modified system having channel type combustion chamber wall. This CFD analysis also shows that both the modified systems can be successfully used for the drying of silk cocoons as combustion gases leave the vessel heating chamber at almost 890 K.

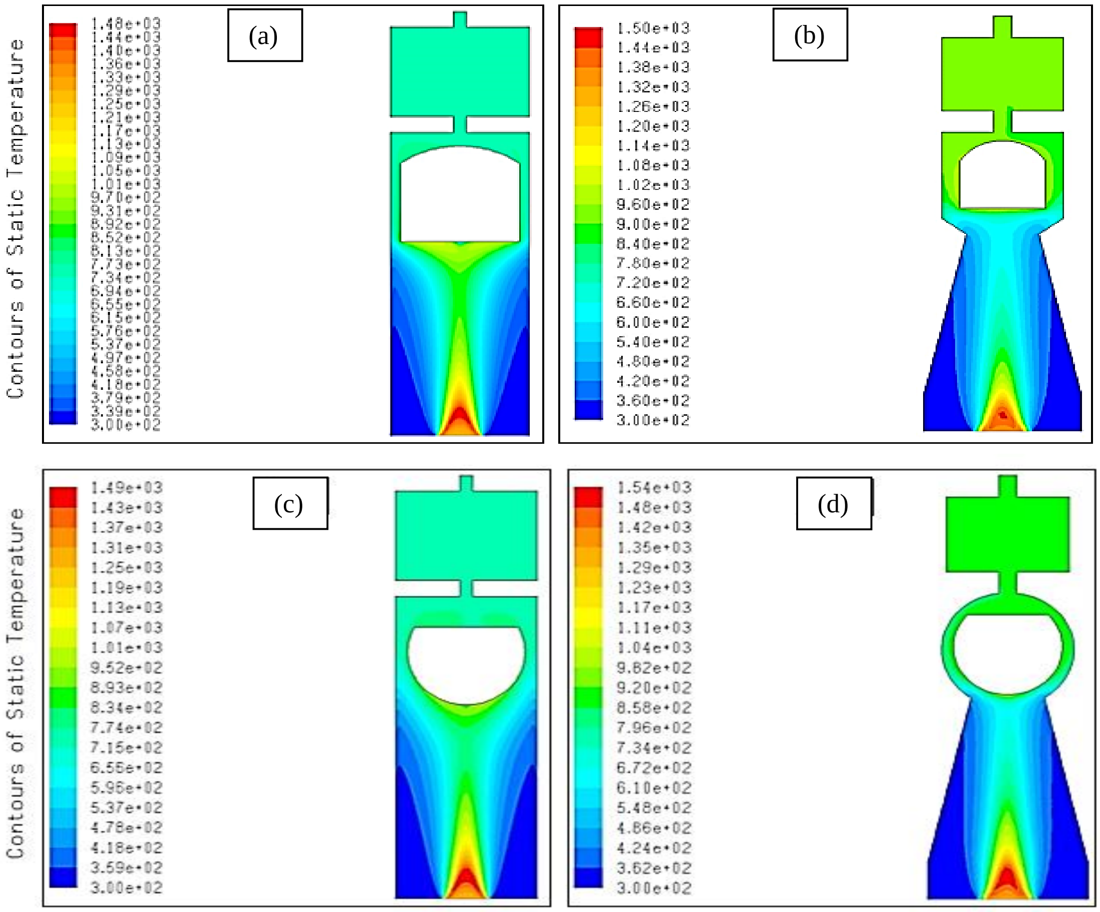

Figure 5. **Contours of static temperature (K) for the four different modified systems.**

From Figures 6 (a) and (b), it can be seen that the velocity of the combustion gases (24 m/s) of the modified system having nozzle type combustion chamber is more than the velocity of the combustion gases (23.2 m/s) of the modified system having channel type combustion chamber. Again, from Figures 6 (c) and (d), it can be observed that the velocity of the combustion gases (23.3 m/s) of the modified system having nozzle type combustion chamber is more than the velocity of the combustion gases (22.1 m/s) of the modified system having channel type combustion chamber. This means that the fluid friction will be more in case of modified system having nozzle type combustion chamber which will heat up the cooking vessel more rapidly than the modified system having channel type combustion chamber. All these results from the CFD analysis of the four different modified systems have been shown in Table 1.

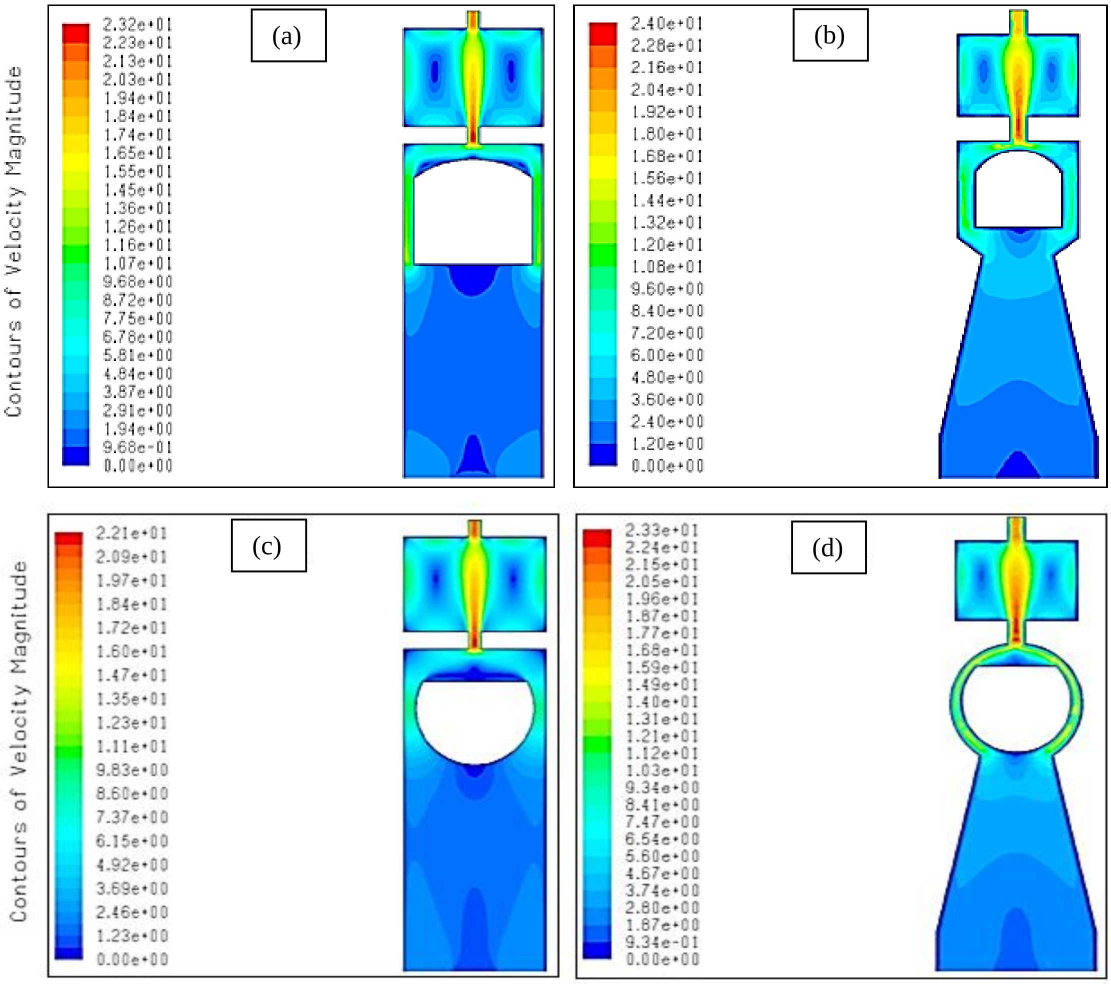

Figure 6. Contours of velocity (m/s) for the four different modified systems.

Table 1. Results from the CFD analysis of the four different modified systems.

Parameters	Modified system having Channel type combustion chamber and cylindrical boiling chamber	Modified system having Nozzle type combustion chamber and cylindrical boiling chamber	Modified system having Channel type combustion chamber and spherical boiling chamber	Modified system having Nozzle type combustion chamber and spherical boiling chamber
Maximum temperature	1480 K	1500 K	1490 K	1540 K
Bottom Wall temperature	1060 K	1070 K	1070 K	1080 K
Side wall temperature	636 K	696 K	654 K	704 K
Temperature at the outlet of vessel heating chamber	876 K	880 K	890 K	892 K
Velocity of combustion gases	23.2 m/s	24 m/s	22.1 m/s	23.3 m/s

5- Conclusions

From this present CFD analysis regarding the cooking and drying of Muga silk cocoons we can conclude the followings:

- CFD analysis shows that in case of cylindrical boiling chamber, the modified system having nozzle type combustion chamber has higher wall temperature (1070 K) as compared to the wall temperature (1060 K) of the modified system having channel type combustion chamber wall for same amount of wood burnt. This means cooking vessel will get heated up faster in the modified system having nozzle type combustion chamber.

- It is also observed that the modified system having nozzle type combustion chamber has higher side wall temperature (696 K) as compared to the side wall temperature (636 K) of the modified system having channel type combustion chamber wall for same amount of wood burnt. This also shows that cooking vessel will get heated up faster in the modified system having nozzle type combustion chamber.
- The velocity of the combustion gases (24 m/s) of the modified system having nozzle type combustion chamber is more than the velocity of the combustion gases (23.2 m/s) of the modified system having channel type combustion chamber. This means that the fluid friction will be more in case of modified system having nozzle type combustion chamber which will heat up the cooking vessel more rapidly than the modified system having channel type combustion chamber.
- CFD analysis shows in case of spherical boiling chamber, the modified system having nozzle type combustion chamber has higher wall temperature (1080 K) as compared to the wall temperature (1070 K) of the modified system having channel type combustion chamber wall for same amount of wood burnt.
- It has been noticed that the modified system having nozzle type combustion chamber has higher side wall temperature (704 K) as compared to the side wall temperature (654 K) of the modified system having channel type combustion chamber wall for same amount of wood burnt.
- The velocity of the combustion gases (23.3 m/s) of the modified system having nozzle type combustion chamber is more than the velocity of the combustion gases (22.1 m/s) of the modified system having channel type combustion chamber.
- CFD analysis also shows that both the modified systems can be successfully used for the drying of silk cocoons as combustion gases leave the vessel heating chamber at almost 890 K.

Thus, it can be concluded that these new systems having nozzle type combustion chambers are more efficient than the systems having cylindrical combustion chambers and if these systems are used in silk production, it will be very beneficial for the production of silk as well as for our society.

6- Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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