Performance Investigation of Novel Improved Cooking Stove Model for Cold Rural Population

By

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Reg # 00000274588

Session 2018-20

Supervised by

Dr. Naveed Ahmed

U.S.– Pakistan Center for Advanced Studies in Energy (USPCAS-E)

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Mr. Ahmad Bin Ayaz, (Registration No. 00000274588)** of Center for Advanced Studies in Energy, has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within similarities indices limit and accepted as partial fulfilment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar and co-supervisor have also been incorporated in the said thesis.

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Abstract

More than 2.6 billion people throughout the world still lack access to clean cooking facilities, despite the robotic era of our technological world. Cooking on traditional stoves causes home air pollution from cooking smoke, which contributes to the 2.5 million premature deaths worldwide each year. In Pakistan 50.8% of the total population use traditional methods to cook by burning wood, animal manure and agricultural residue causing enormous greenhouse gases emissions. . These emissions contribute to the spread of illnesses. . An improved cooking stove (ICS) is one of the finest solutions to this problem, especially in Pakistan's northern regions such as Gilgit, Baltistan, Ghizer, Skardu, and Ghance districts. ICS aids in complete combustion of biomass fuel to decrease hazardous gas emissions, improving overall efficiency, and lowering fuel consumption is proposed in the current studies for. The goal of this research was to design, fabricate, and test a Double Mouth ICS with a chimney and a hot water tank. The design was finalized after taking into account a variety of engineering and non-engineering factors such as material, cost, safety, portability, size, fuel efficiency, fuel type, and interior air quality. Specific features were also included, such as a secondary burner for baking and a hot water tank to maximize waste heat recovery. 3D CAD modeling for development and manufacturing of prototype was done using Solidworks. The temperature distribution and heat flow from the stoves to the chimney were further checked using thermal simulations through3 different convective heat coefficients on a 3D CAD model using ANSYS. Materials such as mild steel and galvanized iron sheets are used to finish the fabrication. The stove's construction material is chosen to be light and robust for mobility. This ICS will assist individuals in improving their indoor air quality, improving their health, and lowering their fuel costs. The performance evaluation during the experimentation on the prototype and the numerical analysis through thermal simulations for the validation of experimental results show that thermal efficiency, fuel saving, burning rate and fire power durability are promising. Conclusively, proposed ICS can help the communities of developing countries to make their life better in terms of good indoor air quality and better health.

Keywords: Improved cooking stove (ICS); Household Air Pollution; Particulate Matters; Thermal Efficiency; Combustion Efficiency.

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List of Abbreviations

ICS	Improved Cooking Stove
GHG	Green House Gases
GDP	Gross Domestic Product
LPG	Liquefied Petroleum Gas
CO_2	Carbon Dioxide
CO	Carbon Monoxide
NO_2	Nitrogen Dioxide
CH_4	Methane
LED	Light Emitting Diode
UNFCCC	The United Nation Framework Convention on Climate Change
EU	European Union
PM	Particulate Matter
TOE	Ton of Oil Equivalent

List of Publications

1. **Ahmad Ayaz,** Jamsheed Sajid, Naveed Ahmed "Performance Investigation of novel Improved Cooking Stove Model for cold rural population". In 1st International Conference on Energy, Power and Environment (ICEPE-2021). Presented: 11 November 2021

CHAPTER 1

Introduction

1.1 Problem Statement

Hashoo Foundation is a not-for-profit organization committed to working with multiple stakeholders and communities irrespective of race, caste, gender, faith or creed. Hashoo Foundation have been working for years for the welfare and development of people of unprivileged areas of Pakistan. They have identified the issue related to Household air pollution (HAP) and the health issues related to indoor air quality. They have found that the main cause of this issue is due to the traditional cooking methods and non-standardized cooking stoves that are being used for years in undeveloped areas of Pakistan. So, a research is required to be carried out in order to address this issue and an improved cooking stove model along with prototype is required to investigate its performance. The areas of Gilgit Baltistan are addressed in this research so the parameters should meet the operating conditions of the area.

1.2 Background

Energy is basic need to carry out daily life activities such as walking, running, powering of house appliances, domestic heating, driving a car and cooking food etc. In simple words, energy can be described as main driving force to do any type of work **[1].** According to energy conservation law, energy in universe is conserved and changes from one form to another. So energy is not consumed in actual rather it changes its states.

World population is increasing and advancement in industrialization, urbanization and better life style is resulting into increased energy demand especially in developing countries. Conventional energy sources are based on fossil fuels. Fossil fuels are major energy source for electricity sector, industrial sector, transport sector, domestic heating and cooking. Fossil fuel burning results into harmful emissions such as carbon mono-oxide, carbon oxide and hydrogen sulfide etc. These emissions are not environmental friendly at all. Carbon dioxide is major GHG gas which is responsible for climatic changes such as melting of polar ice, rising of global temperature and acid rains. So, while supplying the energy to end users, the climatic changes and sustainability of energy must be of primary concern. Energy supply must be reliable, affordable, sustainable and emissions free or at least with very limited emission which will bring positive impacts not only on countries GDP but also on environment [2].

All services and products such as light bulbs, computers, refrigerators, air conditioners and washing machines etc. are dependent on reliable as well as affordable energy supply. If energy is affordable and reliable then products will be easily available in market with affordable price and services will also be easily accessible that will lead to better life style and extended life. When it comes to under developing countries, then energy security and affordable prices become critical as in otherwise case it can cost lives in hospitals and medical centers. In poor countries, energy supply will help in food products availability and access that can prevent mal nutrition and under nutrition as energy play vital role in agriculture services stating from plowing and watering to harvesting. Similarly, international trade is solely dependent on reliable energy supply in transport sector which help in distribution of basic human needs to the deprived areas. Today, hydrocarbons provide the majority of the world's energy, with crude oil serving as the primary source of transportation fuels. Despite substantial improvements in energy efficiency, worldwide energy demand is anticipated to increase by nearly 25% between 2014 and 2040[3].

Energy is required for human progress in a variety of ways, including hospitals, transportation, and access to information, communication technologies, domestic lighting, domestic heating, and food processing. As a result, energy poverty has major ramifications for basic human necessities like food cooking, space heating, lighting, and media access. The overall number of fundamental energies needs in the World scenario is six, based on the use of energy in homes. These six classes of fundamental energy needs for Honduran families are depicted in Figure 1 [4].

1.3 Energy Efficiency Measures

House hold application are dependent on fossil fuels for electricity to power appliances or on fuel for cooking food and space heating. Operation of these households results into harmful emissions such as CO_2 and CO that not only contribute to global GHG emissions but also cause lowering of kitchen air quality index that can lead to premature deaths and other respiratory diseases. In European countries, building sector energy consumption is 40% of TPEC and contribute 36 % of total EU GHG emissions. Reports have suggested that by 2035, the TPEC of domestic sector in UK for households will rise by 11 % with respect to TPEC in 2015. Contrary, fossil fuels prices are increasing and their reserves are depleting which calls for immediate and radical steps to be taken otherwise the gap in energy demand and energy supply will continue to increase and may result into collapsing of energy consuming sector especially industries and domestic sector.

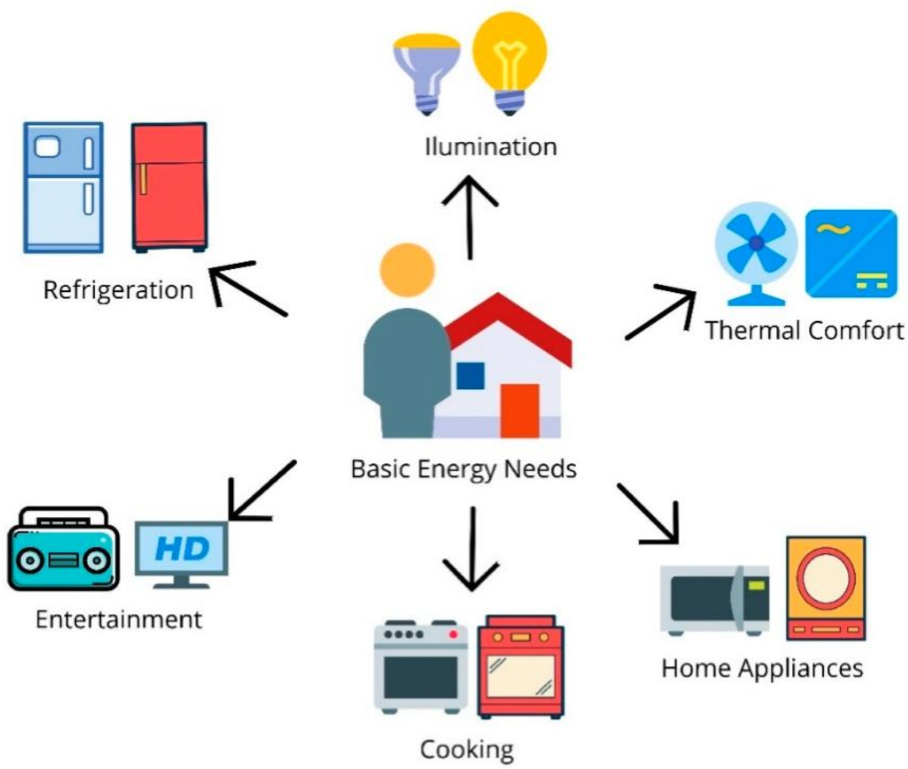

Figure 1- 1 Different ways of energy use in a household

Thus only two significant solution seems to be helping. One is to explore alternative and renewable energy sources such solar, wind, geothermal, hydrogen energy, biofuels and tidal energy etc. These renewable energy sources are locally available in all over the world, they are green energy sources and the will never exhaust. Second substantial step that can be taken to overcome this energy gap issue is by reducing energy demand by conserving energy and using the available energy efficiently. This efficient use energy use will also help to reduce GHG emissions and energy cost. Domestically, reduced energy consumption will help in family financial saving that could be used on children education and for their better health. At domestic level different steps that can be taken to reduce the energy consumption are as follow [5] [6].

1.3.1 Uses of energy efficient devices [7]

- LED bulbs should be used instead of conventional bulbs.
- Efficient fans instead of conventional fans
- LED screen use instead of Desktop.
- GRE Inverex Air conditioners should be used instead of conventional air conditioner which will reduce energy consumption largely.

1.3.2 Solar Day Lighting [8]

- Maximum use of day light hours.
- Building Architecture should be such that we may perceive maximum light and we need to use minimum LED bulb.

1.3.3 Hanging Overs [9]

By using hangovers, at particular angle we can make them useful in both seasons, summer as well as winter. During summer sun declination angle decrease so sun tends to be upward. In this season, hanging overs will not allow the sunlight to fall on building rather hanging over will provide shade which will keep building cool. While during winter, sun declination position is bit down than hanging overs so sunlight will be able to enter into building and provide heat during winter. Thus hanging over will reduce energy consumption by reducing heating and cooling load.

1.3.4 Change in behavior [9]

- Use of sunlight to get the clothes dry instead of dryer.
- Turn OFF lights and Fans when leaving room.
- Unused devices must be plugged OFF.

1.3.5 Reduced Heating and Cooling Load [10]

- Changing the air filters regularly
- Compact sealing of room to avoid any sort of leakages
- Up-gradation and Inspection of walls insulation
- Use of glazed glass windows
- By using thermostats that can be programmed

1.3.6 Use of improved cooking stoves [11]

These days improved cooking stoves designs (ICS) are becoming popular especially in rural areas where solid biomass is used for water heating and food cooking. Conventional biomass cooking stoves are not efficient regarding fuel consumption and reducing emissions as compared to upgraded cooking stoves [12].

1.4 Burning of Fossil Fuels

Since existence of life on this earth, wood have been used as cooking fuel. The turning point from pre-human to human existence is thought to be able to control the fire [13]. Humans have been using biomass left overs and dried animal waste since last 10,000 years for burning and cooking as well as heating of water. Use of coal started back in 10^{th} century when its mining became easy and safe. However, even today, 40 % of human population is still dependent on wood, biomass and coal for carrying out their domestic heating and cooking needs. These fuels are no environmental friendly and result into huge amount of indoor and outdoor emissions especially when burnt inefficiently [14].

Figure 1- 2 Traditional Stove

Then in 18th century, natural gas, LPG and other cleaner fuels were started to be used as cooking fuel. However, it could not make much difference. Even these days 3 billion global population is still dependent on solid fuels.

1.5 Effect on health by burning of traditional Fuels

Unlike coal, fuel wood don't emit much emissions but a fraction of hydrocarbons is not completely burnt that's why the complete and efficient burning of fuel wood in conventional burner is tough. Carbon dioxide and Carbon monoxide are most common products of fossil fuel's burning. Generally, 20 % carbon present in any fuel gets converted into CO_2 and CO. mostly, CO dominates the emissions by mass during fossil fuels burning however, smoke produced during burning of wood contains many compounds other than CO such as polycyclic aromatic compounds, compounds of benzene and dioxin etc. These emissions have serious health concerns on women, cooking food in kitchen especially in case of indoor kitchens [15]. Smoke generated as result of biomass burning contains a wide spectrum of compounds for which Particulate matter with size 2.5 micro meter and carbon mono-oxide are only indications [16][17].

Figure 1- 3 Burning of Wood in Conventional Stoves

1.6 Need of the Modern Stove

In conventional cooking stoves, the combustion is not idea. Most part of fuel wood undergoes partial combustion resulting into products of partial combustion such as fine particulate matter, CO_2, black carbon, N_2O, CH_4, polycyclic hydrocarbons and CO etc. these emissions of real concern as they are responsible for not only climatic change and global warming but serious health concerns especially for women cooking in kitchen. This inefficient burning of wood in stoves is causing 1.6 million deaths in indoor each year according to WHO [18]. So there is need to look for those stoves which may efficiently burn the fuel wood and reduce the toxic emissions. Researchers are trying to find new designs of cooking stoves that are efficient and cleaner in burning [19].

1.7 Other benefits on human health

Other advantages of expanded usage of better biomass stoves include reducing the burden of fuel collection on women and children, allowing women to devote more time to other activities, particularly income-generating activities. Reduced fuel collection periods can also mean more time for rural children, particularly girls, to attend school. The availability of more efficient stoves can help to alleviate respiratory health issues caused by smoke from biofuel burners. Improved mud-based cook stoves were designed and developed, allowing for increased thermal efficiency and smoke removal safety. Improved mud-based cook stoves, on the other hand, need cleaning as well as polishing with regular interval of time. This polishing is done by using mixture of mud and dung. This may lead to irregular shape of stove some time and supply of air to stove may be disturbed, that reduce the thermal efficiency of stove [20][21].

1.8 Scope of Study

Scope of the research has been set to achieve the following objectives:

a) Improvement in combustion efficiency to reduce smoke and harmful emissions.
b) Improvement in heat transfer efficiency to achieve optimum heat utilization.
c) Optimized heat transfer in the pots and heat trapping.
d) Maximum waste heat recovery.
e) Handling of stove i.e. portability and safety.
f) The social & environmental aspects like: cooking norms, type of biomass fuel, heating needs of cold hilly areas, efficient and smokeless room heating, fuel saving, reducing indoor air pollution were given due consideration.
g) Both engineering and non-engineering parameters must be taken under consideration while designing the ICS model.
h) The skill level of the local fabricators was also looked into so as to manufacture locally.

1.9 Organization of the thesis

The following is a synopsis of the thesis proceedings.

- Chapter 2 – Literature Review
- Chapter 3 – Methodology
- Chapter 4 – Results and Discussion
- Chapter 5 – Conclusion and Recommendations

Summary

This chapter includes the problem statement that where the concept of the research has been taken. Hashoo Foundation has funded the manufacturing of prototype of ICS design. Moreover, background of the relative studies have been described which followed by the energy efficiency measures which has been taken under consideration. These measures can be defines as uses of energy efficient devices, solar day lighting, hanging overs, change in behavior, reduced heating and cooling loads and use of improved cooking stoves. Burning of fossil fuels while cooking food causes adverse effects on the health of human being if they are not being utilized or burned properly. Thus creating the need of modern cooking stoves which can burn fossil fuel in more effective and efficient manner. Hence, generating more heat with less production of household air pollutants and greenhouse gases. These modern ICS also have some other benefits which are also presented in this chapter along with the scope of study and synopsis of the research.

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CHAPTER 2

Literature Review

2.1 Why there is need to conserve energy

The greenhouse effect is necessary for life on earth as it is the cycle that sustain the life of living being on earth. The greenhouse effect is a naturally occurring phenomena in which the earth's surface traps the radiation coming from the sun and the temperature of earth's surface rises. The lower atmospheric layer of earth called troposphere where life exist in the form of plants, animals and humans, weather and greenhouse effect occur. This greenhouse effect keeps the surface of earth warmer up to an average of 14°C, without this effect the temperature could reduce to -19°C. Greenhouse gases (GHG) are responsible for this Greenhouse effect. Those gases that absorb the radiations coming from the sun and emits it in the infrared region are called Greenhouse Gases (GHGs). GHG traces are present in the troposphere produce naturally and anthropogenically. Water vapor, Carbon dioxide (CO_2), methane (CH_4), Nitrous oxide(N_xO) and ozone (O_3) are the most abundant greenhouse gases vary with season and annually[1] The United Nation Framework Convention on Climate Change (UNFCCC) focus on environmental degradation due to GHG emission, it emphasizes the stabilization of GHG emission in environment up to a limit within a time frame and its effect on environment disturbing natural processes [2] This convention laid the foundation of Kyoto protocol and Paris Agreement. Countries have decided to reduce these emissions. 182 countries of the world and the EU, have agreed on Kyoto protocol. The application of this protocol started in 2005 defining timelines and targets for these economies to reduce greenhouse gas emissions into the atmosphere by implying legal limit of emissions[3].

2.2 Paris Agreement

Paris agreement signed by 195 countries, take climate change as a potential threat for the environment and the planet. It says to maintain the average temperature increase below 2° Celsius and try to limit it to 1.5° Celsius. It also focuses to help and finance the developing countries, which will be mostly affected by the adverse effect of climate change. After every five years, the progress and the measure taken to preserve the environment are reviewed and ambitions are risen.

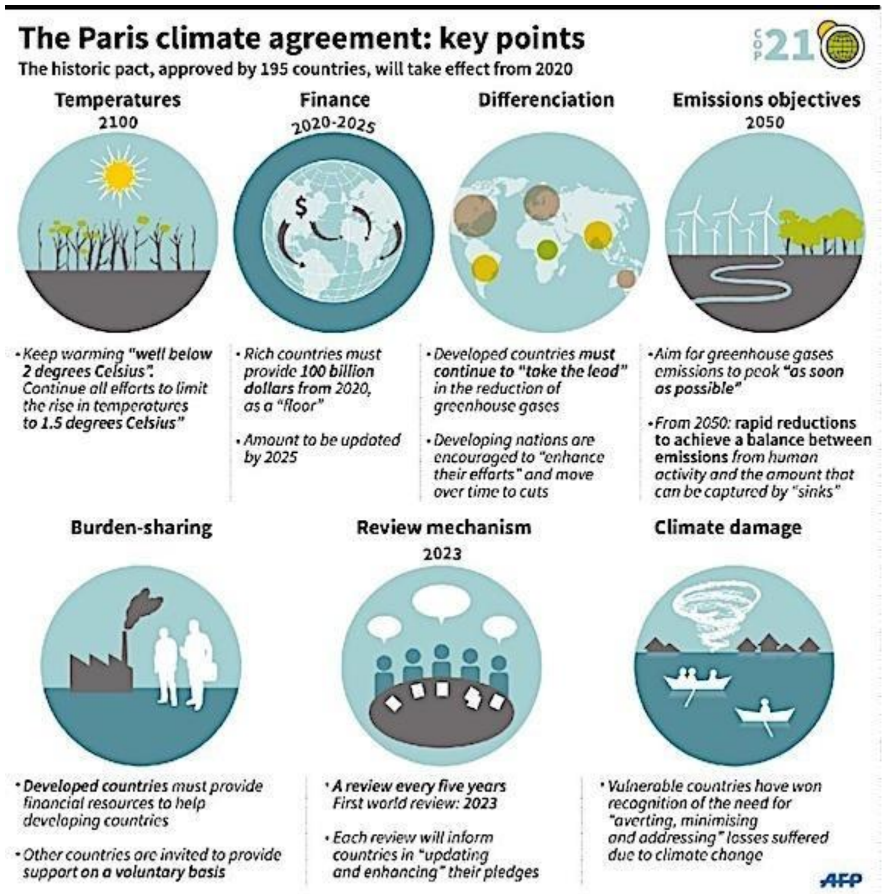

Figure 2- 1 Paris Agreement Key Points

2.3 Energy Efficiency Measures

Energy efficiency measures can help to reduce the energy demand in winter and also in summer. It includes use of energy efficient electrical devices, change in utilization behavior of devices such as reduction of thermostat setting by one degree, building architectures to maximize the use of daylight and sustainable buildings and use of improved cooking stove designs to reduce natural gas consumption or wooden biomass consumption. Due to energy efficiency measures and increase in conversion efficiency, the reduction in cumulative emissions by 2050 will be at-least 94% than reference case [4]. Figure 1 shows the reduction in CO_2 with respect to reference case. In reference case the cumulative CO_2 emissions will be 35Gt/year in 2050.

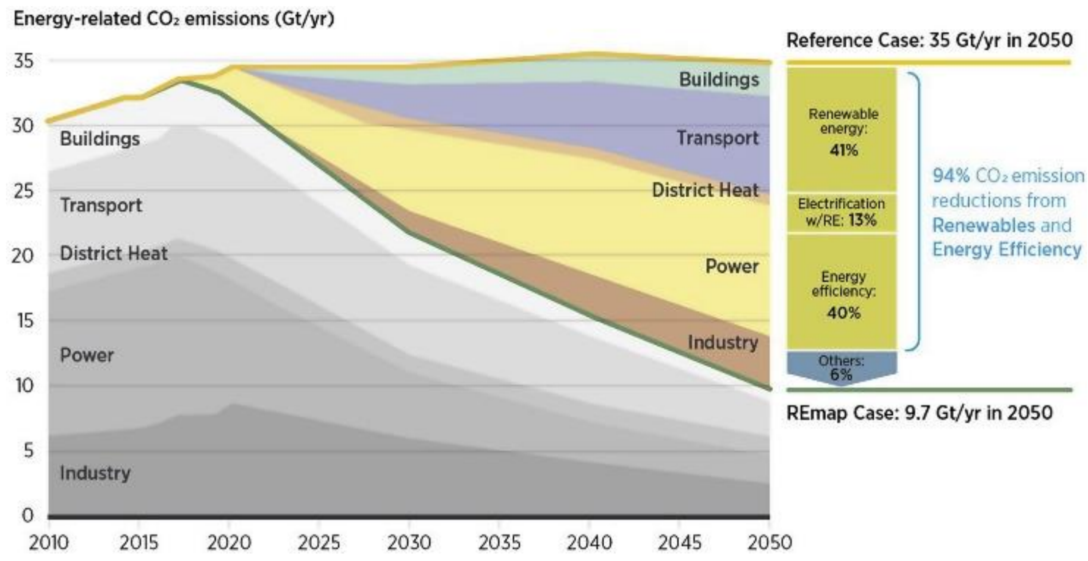

Figure 2- 2 CO_2 Emission Reduction in RE map [5]

2.4 Biomass and Fuel Wood Scenario in Pakistan

In most of rural areas of Pakistan, biomass, animal waste and fuel wood are major energy source for cooking and heating. On average in Pakistan biomass use by a household is 2325 kg fuel wood per annum along with 1480 kg animal waste and 1160 crop waste. By 1992, consumption of biomass in Pakistan was 19,256 TOE which is equivalent to 27 % of Pakistan TPEC. This biomass share increased to 39 % by 1994. However, due to technological improvement by 2003, biomass share in TPEC reduced to 23.5 %. Keeping in view this high biomass consumption in Pakistani rural area, Improved Cooking Stove (ICS) are of key importance. Pakistan Council for Renewable Energy has installed 60,000 ICS in all over Pakistan having burning efficiency of till 28 % [5].

2.5 Fuel wood and Cooking Stoves

Various assessment reports have revealed that the fuel wood supply is going to face a serious issue of shortage in future especially in developing countries where people rely on fuel wood for their cooking and heating energy demand. Approximately half of world population is living in those areas having scarcity of fuel wood supply. According to World Bank reports, the annual consumption rate of forests for fuel wood is 1.3 %. The radical measurements taken so far include tree plantation and reforestation. However, these measurements are not meant for ease of this crisis in near future. The demand of fuel wood supply can be reduced by reducing the fuel wood consumption by employing efficient cooking stoves designs that will efficiently burn the wood and will reduce the GHG emissions as well. As reported by Joseph et al. [6], approximately 100 different scales programs of stoves have been employed for efficient burning of fuel wood. The primary objective of improved cooking stoves (ICS) especially in rural areas is to conserve the energy. ICS can reduce the fuel wood consumption by 50% for cooking. In villages of African and India, the energy consumption provided by fuel wood is 60% and 80% respectively. In countries like Mali and Nepal, share of fuel wood in final energy consumption is 90%. Developing countries are also no exception in this regard. The share of fuel wood in energy consumption of developing countries varies between 30-80%. ICS are required to inhibit the open fire that results into smoky atmosphere, kitchen dirtiness, bad food taste and other respiratory diseases [7].

2.6 Improved Cooking Stoves (ICS)

ICS will not only reduce the energy consumption but also it will bring many positive ecological impacts which includes slowing down of many negative ecological phenomena which include:

- Erosion
- Organic conditioning materials (In case of wood supply people won't use animal manure and crop waste)
- Deprivation of soil nutrients
- Siltation
- Desertification.

In rural areas, the ICS will help to reduce the drudgery of wood collection or reduced burden of purchasing fuel wood. It will eventually help to reduce human resources use and financial expenditures. Women going for kilometers away for wood collection will have more time for the education and nutrition of their children. In case of fuel wood purchase, 40% of house expenditures will be reduced with ICS [8][9][10].

2.7 Stoves Categories

Usually the major categories of stoves are [11][12]:

Shielded light weight (All metallic and Ceramic Stoves that are portable)

Shielded heavy weight (Concrete, Mud, Sand, Clay and Brick Stoves)

Closed heavy weight (Fire doors, chimneys and Damps)

Figure 2- 3 a) Shielded Light Weight b) Shielded Heavy Weight c) Closed Heavy Weight

2.8 Benefits of ICS

The traditional stoves such as mud, clay and sand stoves are very inefficient and are capable of harnessing only 5-15 % of energy content from fuel. Thus causing comparatively higher damage to environment in term of GHG emissions and loss of economy. Household air pollution is responsible for nearly 4 million deaths due to polluted environment globally per year. Non-traditional stoves such as metallic stoves offer a lot benefits. These benefits vary for each construction design and quality of stoves. Household air pollution is reduced and cooking women have better health quality. Shichang et al. found that due to fuel wood burning in kitchen, total suspended particles in kitchen were 4.45 mg m-3. Toxic emissions concentration in kitchen was 3.16 ugm-3 (Cadmium), 35 ugm-3 (Arsenic) and 81.29 ugm-3 (Lead) resulting into serious health concerns [13]. Harmful emissions due to fuel wood burning result into indoor pollution causing 3.5 million premature deaths while outdoor pollution cause 0.5 million premature death annually [14].

Fuel use is reduced significantly which in turn reduce the amount of GHG emissions. Less fuel usage means lower house expenditures in case of commercial fuel and less time spent in collection of fuel woods. Moreover, less cleaning of pots and cooking clothes will be required in case of non-traditional stoves [15]. Even a simple design of ICS can reduce the fuel consumption by 20-30 %. However, due to high capital cost of ICS as compared to conventional stoves, the adoption rate of ICS is low [16].

2.9 Recent Developments in ICS

Armin Altouni et al. [17] developed PV powered induction cooking stove for promoting the clean energy in rural areas. These stoves are environmental friendly, no fuel is required, no flame and safe to use. Power demand induced cooking stoves was being met with electricity produced by off grid solar PV system. Maximum energy efficiency of this off grid PV system was 11.8 %. In this study different design and types of stoves were evaluated in term of rise in temperature and energy transfer after 5 minutes duration. At an voltage input of 45V, the stove made of steel with 13mm diameter and 1mm thickness showed highest heat transfer efficiency with temperature rise of 63 C. Comparison of cooking time for different items for different fuel types was investigated and it was found that for most of cooking items, the cooking time required in case of LPG stove is less than PV induced cooking stove while electric stove were found to be having highest cooking time. With PV cooking stove, the cooking cost for whole one month was calculated to be 3.88 USD.

Figure 2- 4 PV Induced Cooking Stove

Table 2- 1 Comparison of Different Types of Stoves

Stove Type	**Energy Source**	**Air Pollution**	**Efficiency**	**Safety**
Traditional	Biomass	Very High Emissions	35-45 %	Very low
LPG	LPG	High Emissions	48-58 %	Low
Electrical	Electricity	Low Emissions	50-85 %	Medium
PV Induced Cooking stove	Solar Energy	No Emissions	Till 90 %	High

Aneeq et al. [18] investigated the thermal properties of ICS. This ICS construction design was made up of mud with height, width and length of 10 in, 16 in and 32 in respectively. A twin mouth cooking burner having chimney to exhaust the gases was the design of stove. Water boiling test with 4862 g water was applied on stove to test the stove design. The caloric value of wood used in experimentation was 17.39 KJ/kg. Air thermal conductivity was 0.029 W/m.K and specific heat of water was 4.18 j/g.K. Specific fuel consumption was 60 g/litre of water and water boiling rate was 11.1 min/liter. With 293 g of fuel consumption, the efficiency of stove was found to be 30 % which is very comparable to those of efficiencies being claimed for ICS for biomass combustion.

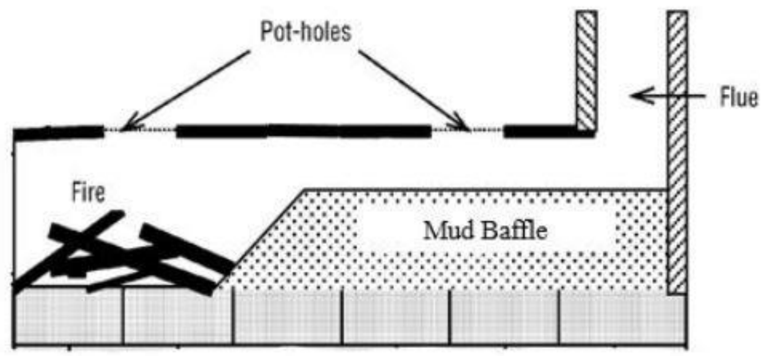

Figure 2- 5 Pictorial View of Designed ICS

Anoop singh et al. [19] investigated the analysis of experimental and computation of cooking stoves being used in homes. Comparison of single and double layer porous radiant burner was investigated. In case of single layer porous burner, required heat input was 5-10 kW. Burning efficiency was found to be 30-40 %. The carbon mono-oxide emissions were ranging between 350-1145 PPM while NOx emissions were ranging between 40-104 PPM. In case of double layer porous burner design, required heat input was 1-3 kW with NOx emissions of 0.2-36 PPM while carbon monoxide emissions were ranging between 30-140 PPM. The efficiency of double layer porous burner design was found to be 75.1 %.

Most of ICS don't address the institutional scale cooking especially for rural customers who mostly depend on biomass for cooking and heating. Benjamin et al. designed and implemented an institutional ICS to overcome this gap and implemented this IICS in Nepal. The manufacturing and testing of this IICS was performed in government approved testing center and studied the various complex factors affecting the performance of ICS. With 25.5 kW firepower, the IICS stove efficiency was found to be 59 % at burning rate of 20-83 g/min.

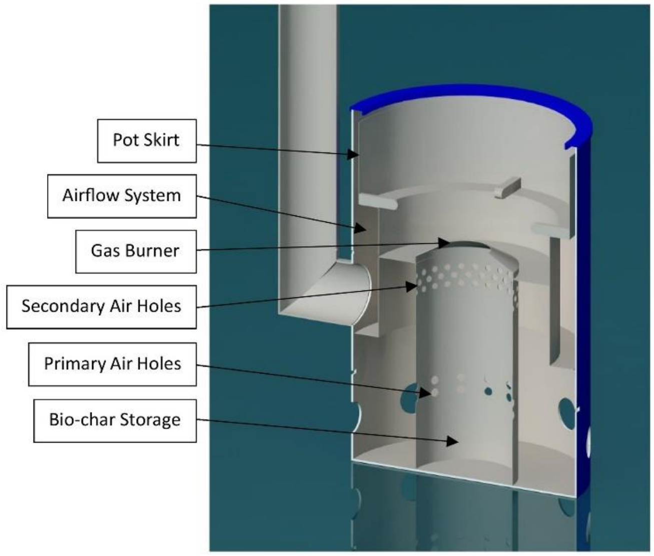

Figure 2- 6 Working Design of IICS

Fernando Manzano et al. [9] studied the use of biomass for cooking with conventional stoves and improved cooking stoves in Mexico. Use of biomass increased from 13.7 % in 2006 to 13.9 % in 2018. Thus ICS use in Mexico is of significant importance. ICS use for biomass burning in Mexico 2.1 % in 2000 which reduced to 1.9 % in 2006 due to technological barrier and higher capital cost of ICS. With advancement in design, and bulk production resulting into reduced cost of ICS, the use of ICS in Mexico increased to 2.4 % by 2018.

Peter Nuhu et al. [8] worked for improving the cooking stoves design in Ghana. The purpose of this study was to promote the ICS in Ghana and reduce the fuel cost as well as GHG emissions. Different mathematical models were used and equations were derived to investigate the comparison of cost and GHG emission when Ghana cooking stoves are replaced with ICS. Comparisons was made between wood, charcoal and LPG Improved cooking stoves. In term of private benefits, these designs were proved to be having negative benefits. Negative benefits for wood stove was USD 0.81 per month. For Charcoal these negative benefits were 0.42 USD per month while for LPG ICS these negative private benefits were 0.89 USD per month. However ecological benefits were positive. These Positive benefits for wood stove were USD 5.70 per month. For Charcoal these ecological benefits were 1.09 USD per month while for LPG ICS these negative private benefits were 33.5 USD per month.

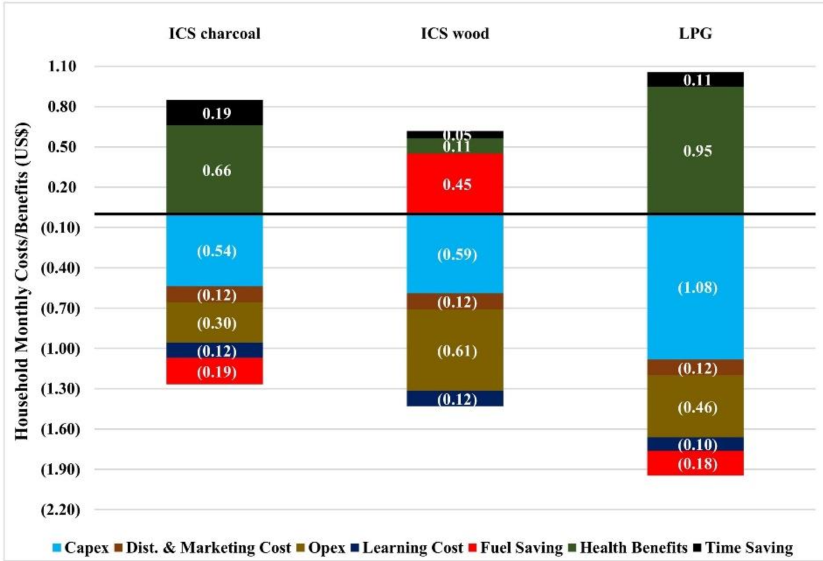

Figure 2- 7 Cost and Benefit Comparison of 3 types of stoves

Wilfredo C. Flores et al. [20] analyzed the Honduras national strategy in term of cost benefit as well as energy consumption for ICS. LEAP software for used for modeling and analysis of energy policies. LEAP provide analysis of GHG sinks, sources, local air pollutant, regional air pollutants, short-lived climate pollutants and climatic co-benefits. LEAP is capable to take in account both energy and non-energy sector for modeling. The input parameters of energy model were energy demand and ICS introduction stepwise. Results showed that if ICS are not adopted in country then the cost paid in term of health risks due to GHG and purchase of fuel will be higher in comparison with adoption of ICS.

Figure 2- 8 Fuel wood demand in Honduras in BTOE in case of Traditional and Improved Stoves

A.E. Putun et al. [21] stated that in traditional energy use, heat required for cooking food and domestic space heating are very crucial. In upcoming many years, the biomass use is not going to be reduced as biomass use is directly associated with poverty. Currently, world is facing major issue of inflation causing poverty so biomass is priority fuel for poor sector. Also closed carbon cycle of biomass is contributing in sustainable energy development. Thus, ICS market is going to be major market in near future and will have enormous opportunities.

2.10 Reduced Emissions with ICS

N.L. Panwar et al. [22] designed ICS and evaluated it performance using various fuels. This design was tested with babul wood, shell briquettes of ground nuts, briquettes of saw dust and cashew nuts. To reduce the heating losses, insulation of stove was done by using refractory cement. Thermal efficiency of this stove working at 1.53-1.75 kW was found to be 35 %. Emissions related to CO were 3-6 PPM and for CO2 emissions were 17-25 PPM. Maximum temperature of stove was achieved in case of cashew nut as fuel and temperature reading was 763 C.

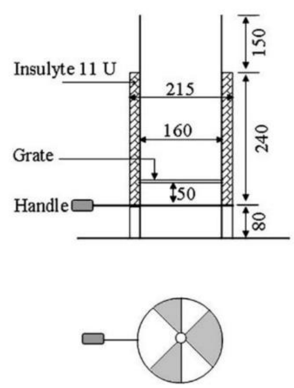

Figure 2- 9 Schematic of ICS

In another study, Panwar et al. [23] evaluated the ICS performance by using Jatropha as fuel. Evaluation test performed was water boiling test to evaluate thermal and emission efficiency. SPRERI gasifiers stove and double pot ICS were used in this study and their efficiency was found to be 31.1 % and 22.88 % respectively. Both of these ICS designs were affordable and durable. In term of emission efficiency, double pot ICS outperformed the SPRERI gasifiers stove.

Omar Masera et al. [24] studied the ICS impact on indoor air quality in Mexico. In Mexico, 4000 improved patsari cook stoves were employed in a community. In kitchen air after 48 hours, CO and CO_2 emissions were reduced by 66% and 67%. Thus ICS helps to reduce indoor air pollution and reduce health costs.

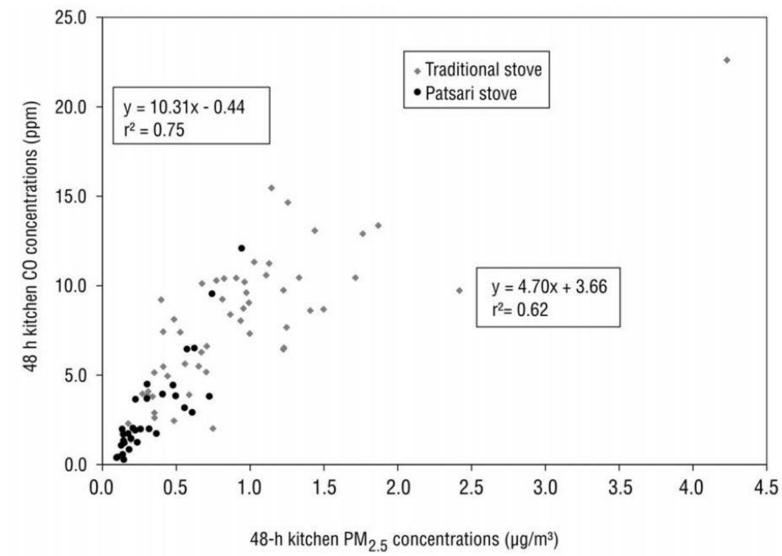

Figure 2- 10 PM concentration in Kitchen after 48 hrs.

S.C Bhattacharya et al. [25] analyzed the experimental data of emissions of charcoal and wood fuel in ICSs. This comparative study revealed that in case of charcoal as fuel, CO, NOx and CO_2 emissions as compared with wood as fuel in ICS. However, CH_4 and TNMOC emissions for both of stoves was more or less same. For both ICS, at higher efficiencies, emissions per joule of use heat were less.

N.S. Rathore et al. [26] investigated the GHG mitigation by using ICS. Single and double pot designs of ICS were used in this study. By using these stoves, concentration of flue gases remains within limits as per WHO parameters. Thermal efficiency of single pot ICS was recorded at 21% while for double pot ICS it was 25%. Results showed that use of these ICS can help to reduce 161 kg of CO_2 emissions annually.

Figure 2- 11 a) Single Pot ICS b) Double Pot ICS

Christoph A. Roden et al. [27] investigated field as well laboratory scale emissions from traditional and ICS. Results of study revealed that the PM emissions during actual cooking in field are 3 times more as compared to that of PM emissions in laboratory. Stove operator skills play major role in concentration of emissions. Single Scattering Albedo for lab test was 0.3 while for field test was 0.5. Use of chimney with ICS help to reduce the emissions further. Emission factor for traditional stove was 8.2 g/kg while for ICS without chimney was 6.6 g/kg and with chimney, this factor further reduced to 4.5 g/kg.

Summary

This chapter elaborates the literature review for the research work. Defining the need for the conservation of energy along with the importance of Paris agreement. Energy efficiency measures has been discussed to highlight the biomass and fuel wood scenario of Pakistan. Consumption of fuel wood and usage of conventional cooking stoves has been argued to understand the importance of need of improved cooking stoves. Various ICS design has been deliberated in order to understand the benefits of ICS and stove categories. Recent development in ICS has been reviewed to have a clear understanding about reduction of emissions with usage of ICS.

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Chapter 03

Methodology

Heat in the ICS is produced by burning of wood or charcoal. This heat is then transferred to the secondary stove and surroundings by all three heat transfer mechanisms. Main purpose of ICS is not only produced cheap and efficient heat but also to make the whole process as smoke free as possible. The theoretical background behind efficient heat transfer is explained below

3.1 Governing mechanism of heat transfer

Heat transfer in an ICS can be explained on basis of thermodynamics laws. All three heat transfer mechanisms namely conduction, convection and radiation as well geometry and local convective conditions determine the behavior of ICS stove. Schematic of these phenomena are explained in Figure 3-1.

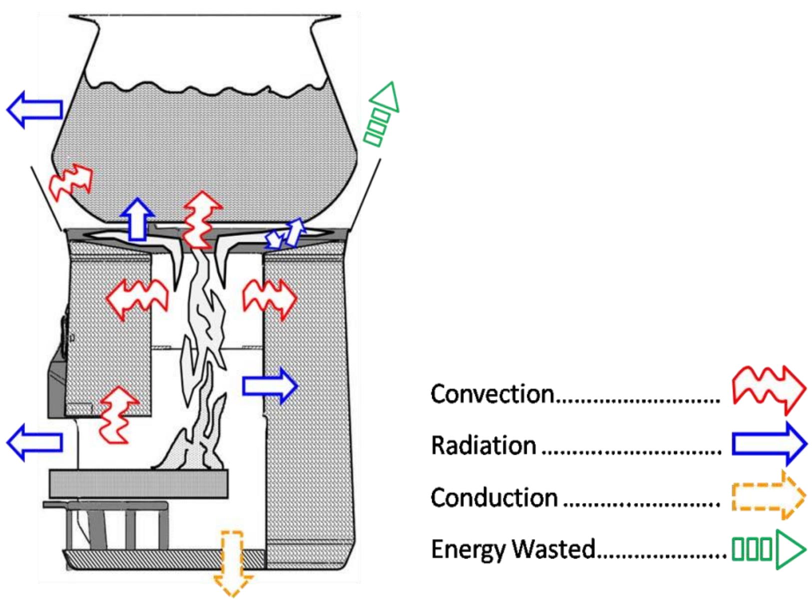

Figure 3- 1 Heat transfer mechanism in ICS

3.1.1 First Law of thermodynamics

The law of thermodynamics is the law of conservation of energy. It states that the total energy of any isolated system (for which energy and matter transfer through the system boundary are not possible) is constant [1]. Energy can be transformed from one form to another, but can be neither created nor destroyed. If an existing ICS is carefully evaluated and modified, all the energy used in the combustion process must be considered. The first law of thermodynamics plays an important role in this assessment as it provides a tool to achieve the ideal balance of energy in cooking. Achieving a precise energy balance is vital to determining the most efficient way to improve stoves. First Law Thermodynamics requires that all energy in a system be conserved, even if it changes form. In the working environment, combustion converts the stored chemical energy of the fuel into heat energy. Some of this thermal energy is taken as flow energy, which passes through a stream of hot flue gases through the heat and across length of stove.

Effective application of the first rule in cooking leads to a better understanding of the principles that govern its work. The first rule is used to perform weight and force balance in a closed or open system. The cooking oven represents an open system because it is exposed to the flow of gases in a limited volume, which is called the volume control. A control boundary can be assumed across control volume, thus heat, work and mass balance can be solved on this system. Control volume description of ICS is shown in Figure 3-2.

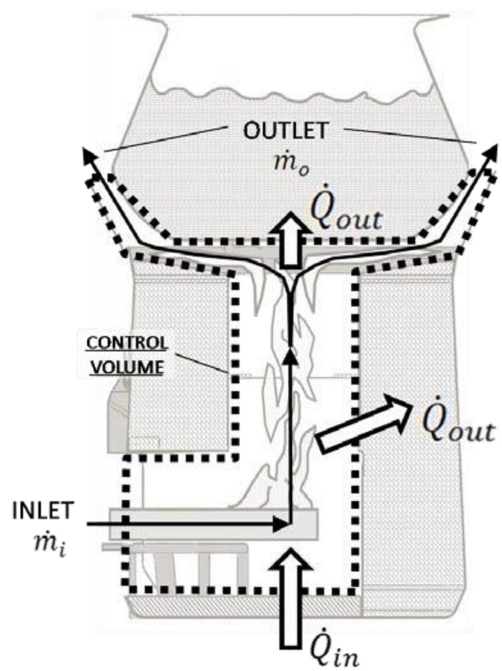

Figure 3- 2 Control volume description of generalized single pot ICS

On the basis of energy and mass balance the governing equation of ICS can be simplified to

$$E_i = E_\circ \qquad (1)$$

$$Q_i - Q_\circ = m\ C_p\ avg(T_\circ - T_i) \qquad (2)$$

Where:

$\dot{Q}$ – rate of heat energy transfer

$\dot{W}$ – rate of work energy transfer

$C_{p,avg}$ – average constant pressure specific heat of air between T_i and T_o T – gas temperature

Interdependency of all the state variable can be seen from mentioned equation. Mass flow rate, temperature and heat in and out of control volume are directly related with each other.

3.2 Heat Transfer Mechanism of ICS

All the three heat transfer mechanisms contribute towards the cooking and heating of environment. The contribution of all though varies. Like radiation contribution is very less but in the long run of things it is a major player. Each mode can be split into gain or loss of energy. The energy lost is the energy that goes into the stove or environment. This will come out as increase in sensible heat. While the heat entering into the ICS like burning of fuel is energy gain [2]. The burning of fuel contributes a fraction of energy into the system. A detail assessment of heat transfer modes is as follows;

3.2.1 Conduction

Conduction is first heat transfer mode that is encounters when fuel is burned on grating plate of primary stove of ICS. The basic conduction equation can be written as

$$Q_{cond} = {(K * A * \Delta T)}/{L} \qquad (3)$$

Where

k = thermal conductivity,

A = cross sectional area of object,

ΔT = temperature difference,

L = object thickness

Now in ICS there are no conduction related losses. ICS is placed on the ground which is often made of mud or clay. The conduction coefficient and contact area is too low to accommodate this loss. So it is assumed adiabatic as far as heat loss to ground through conduction is concerned. Moreover, the thickness of walls of stove are small as compared to their lengths thus making conduction heat transfer negligible.

3.2.2 Convection

Hot gases are produced as by product of burning. These gases have high temperature. They flow into the secondary stove and chimney through connected pipes. These pipes gain heat as the time passes. But the other surface of ICS losses gained heat to surrounding as convection heat loss. The convection equation is written as;

$$Q_{con} = h * A * \Delta T \quad (4)$$

Where

h = convection coefficient (W/m^2K),

A = exposed surface area,

ΔT = temperature difference

Mass flux of flue gases is major factor in convection heat transfer. Other contributing factors are the area of surface of heat transferring body and difference in temperature of that surface and ambient environment. Convective heat transfer increases many folds as the flow velocities are increases and as the temperature difference between body and surrounding increase. As the objective of the ICS is to heat up the surrounding areas, the exposed surface (outer area) of ICS plays an important role in transferring convective heat from stove to surrounding. But there is a limitation to this as increase of area means increase of cost of ICS which has be in an affordable range. Thus the general practice is to focus on increasing the surface area of combustion stoves to expose gases to extended surfaces.

Total convection losses can be accommodated by considering the primary and secondary stove as well as piping areas. Both stoves can be considered complete cylinders with fully developed internal flows. The same assumptions can be made for connecting pipes. Constant mass flow rate and gas temperature can be assumed. Flow in each pipe can be assumed to be in transition between laminar and turbulent. Although the assumption of turbulent flow will also yield better results. Transition or turbulent convective heat transfer coefficient, allow for a rough approximation of convective heat transfer coefficient. The heat transfer coefficient will be different in each stove and pipe segment as sizes of pipes along with temperatures varies. It can well be seen that primary stove will contribute more in convective heat than secondary or piping.

3.2.3 Radiation

Radiation heat transfer occur from burning of fuel or flames. The heat is transferred to the stove body and ambient surroundings. Radiation heat transfer from a black body can modelled by following equation,

$$Q_{rad} = A * \sigma * (T_2^4 - T_1^4) \quad (5)$$

Where

where T_2 and T_1 are the respective temperatures of each surface.

Temperature difference is the main contributing factor in radiation hat transfer. The surface area of emitting body and emissivity and associated view factor are important factors in deciding amount of radiation heat transfer into environment. Increase in each variable increase the radiation heat transfer. View factor is a number which accounts for the amount of radiation that can reach from one surface to another due to their relative orientation.

Radiation heat transfer can be easily calculated for both secondary and primary stoves and their piping. Emissivity of all parts of ICS stove can be assumed to be 0.9 and temperature independent. Radiation loses between the stove and environment can be calculated by assuming grey body assumptions. Radiation heat transfer into the pot comes from three sources, fuel, flames and reflected radiation. Pot surface can be assumed to be a black body for ease of calculations.

3.3 Experimental verification of prototype

The main objective of the project is to analyze the thermal behavior of stove. As discussed earlier the stove needs to be operational in worst case scenarios, like in closed kitchens where there are very little convectional currents. For this purpose, CAD drawings were constructed and from them a prototype model for experimentation was developed. The details of prototype development, experimentations and analysis are given below.

3.4 Development of Porotype ICS

From literature review various designs were considered. From all those designs a prototype design was proposed. This prototype was on 1:1 scale. The conceptual drawings of prototype ICS are shown in Figure 3-3 and Figure 3-4.

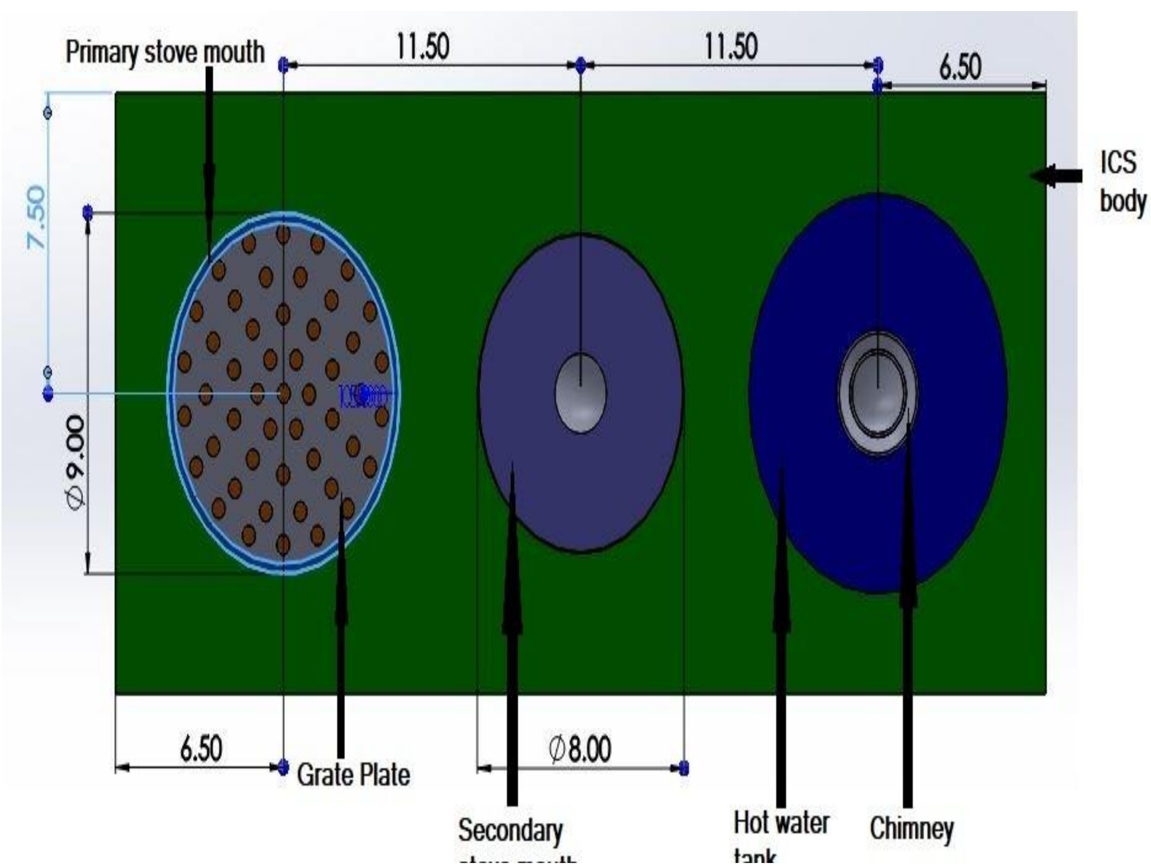

Figure 3- 3 Top view of proposed ICS

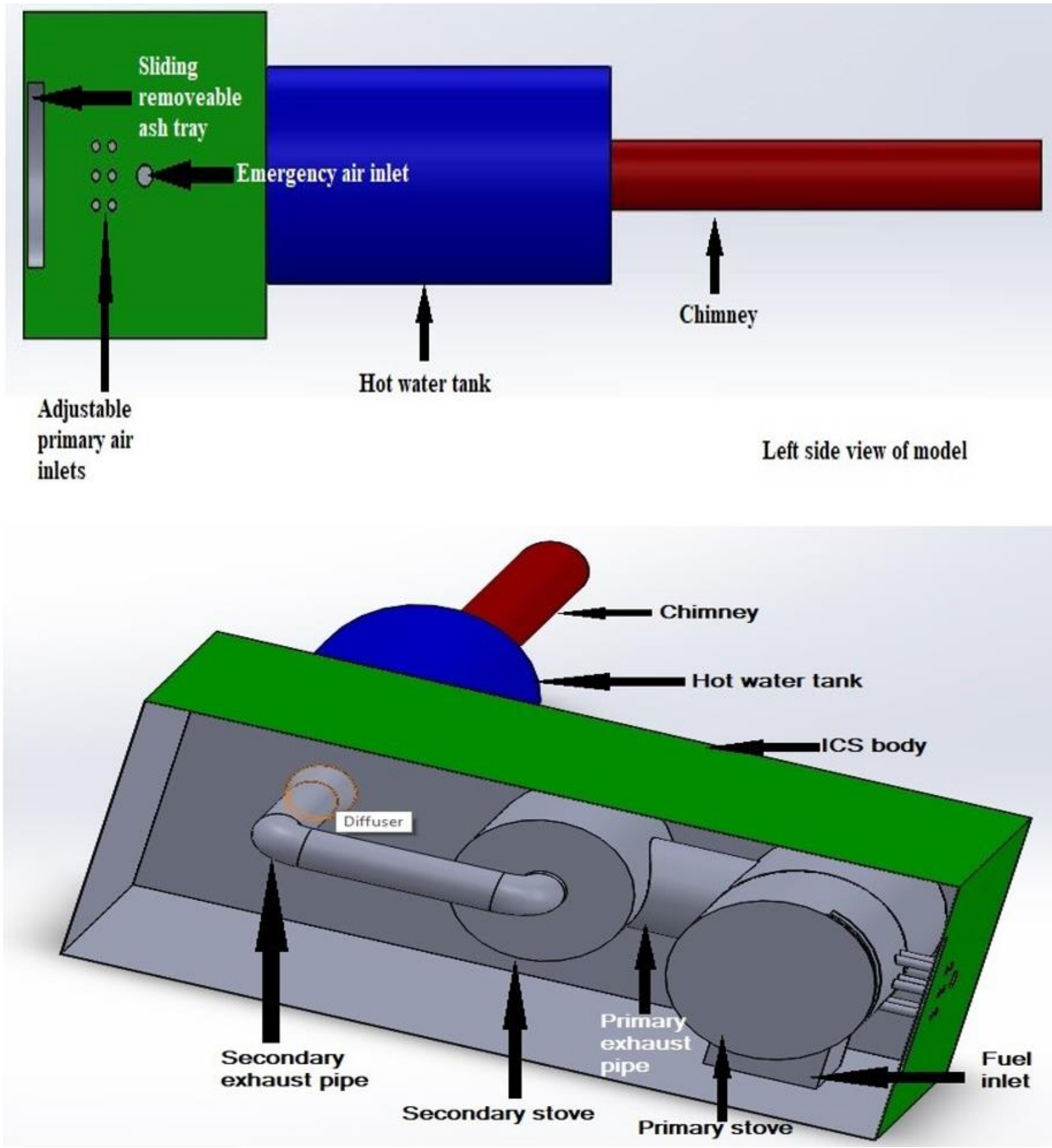

Figure 3- 4 Various views of proposed ICS

As can be seen from the figure the proposed ICS had two mouths where primary cooking will be done. It also has a water tank with opening specifically developed for use in cold rural areas like Gilgit-Baltistan. The capacity of the water tank is 20 liters. This water after drainage from ICS can be used for cooking as well as room heating purpose. The design of the pot also makes less smoke as there are a lot of air inlets. Air enters from the primary inlet and then pass through grating. The separate hole makes the combustion process very efficient. Primary stove is connected to the secondary stove through a pipe. The flue gases then pass to the secondary stove through that pipe. High temperatures can also be achieved in this pot because of these flue gases. The flue gases then pass through pipe section and into the chimney. The chimney is surrounded by water tank where heat is absorbed. The enthalpy of the water rises thus turning it into a heat source. The entire body of the stove is made up of metal thus after some time the radiation as well as convection heat transfer from the surfaces of the stove, exhaust pipes and part of chimney contribute to room heating. The exhaust of the chimney has a control baffle. The baffle can be operated various configurations. In its close confutation it effectively blocks the flue gases thus reducing burning rate and hence controlling the room temperature. The prototype is shown in Figure 3-5. Table 3-1 shows the construction materials along with dimensions of various parts of ICS prototype.

Figure 3- 5 Prototype of developed ICS

Table 3- 1 Construction materials along with dimensions of ICS prototype

Sr. No.	Part Description	Construction Materials	Dimensions
1.	Outer Body	Galvanized Iron Sheet (22 SWG)	15 inches × 36 inches × 15 inches
2.	Primary Stove	Mild Steel sheet (16 SWG)	9 inches dia × 15 inches high
	Secondary Stove	Mild Steel sheet (16 SWG)	8 inches dia × 8.5 inches high
3.	Grate Plate	Mild Steel bar (4 to 5 mm)	9 inches dia × 1 inch thick
4.	Primary Air inlets (× 6)	Mild Steel pipe (16 SWG)	1-inch dia × 2 inches long
5	Primary Air inlets cover	Galvanized Iron Sheet (22 SWG)	3.5 inches × 5 inches
6.	Emergency Air inlet	Mild Steel pipe (16 SWG)	2 inches dia × 2 inches long
7.	Emergency Air inlet	Galvanized Iron Sheet (22 SWG)	2 inches dia
8.	Fuel inlet	Mild Steel sheet (16 SWG)	5 inches × 5 inches
9.	Fuel inlet cover	Galvanized Iron Sheet (22 SWG)	5 inches × 5 inches
10.	Primary Exhaust pipe	Mild Steel pipe (16 SWG)	7 inches dia × 3 inches long
11.	Secondary Exhaust pipe	Mild Steel pipe (16 SWG)	2 inches dia × 6 inches long
12.	Diffuser	Mild Steel sheet (16 SWG)	Tapered 2 inches to 3 inches dia
13.	Chimney	Galvanized Iron Sheet (28 SWG)	3 inches dia × 6 feet high
14.	Baffle	Galvanized Iron Sheet (28 SWG)	Zigzag 6 feet long × 3 inches wide
15.	Hot Water tank	Galvanized Iron Sheet (22 SWG)	Inner dia 3 inches Outer dia 8 inches
16.	Insulation	Mixture of red clay, plaster of paris and saw	2-5 mm thickness
17.	Knobs insulation	Bakelite	Nil

3.5 Experimental Setup

As discussed earlier a prototype model was developed on the basis literature available. The model was tested to check the feasibility and working of model. 1.6 kg of dry wood was burned at primary stove. Open air experimentation was performed as the experimentation could cause file as well as smoke hazard. Time and temperature were recorded at an interval of 8 mins for 56 mins activity. ICS had 7 thermocouples installed on it. Initial conditions along with thermocouples locations is given in table 3-2. The locations of thermocouples are indicated in Figure 3-6.

The experiment ran smoothly. Readings were collected as per set frequency. The experimentation is shown in Figure 3-7.

Table 3- 2 Initial conditions along with thermocouple locations

Ambient temperature	22 °C
Initial ICS body temperature	28.4 °C
Initial water temperature in tank	30.3 °C
Weight of pure dry wood	1.6 kg
Locations of the thermocouples	
Flame temp in primary stove (flame)	T1
Primary stove body temp (body)	T2
Primary exhaust pipe temp (smoke)	T3
Secondary stove body temp (body)	T4
Secondary exhaust pipe temp (smoke)	T5
Water temp in tank (water)	T6
Exhaust exit temp in chimney (smoke)	T7

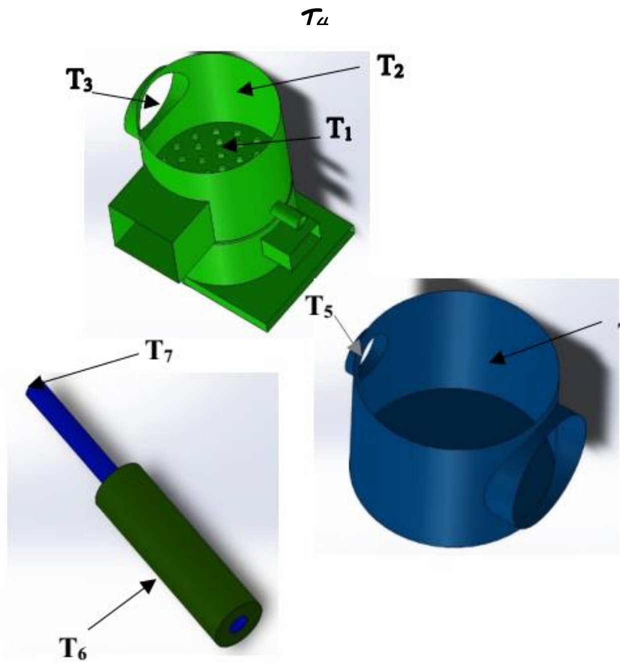

Figure 3- 6 Temperature identification locations

Figure 3- 7 Experimentation of ICS prototype

3.6 Thermal Simulation

For analysis purpose the first step is the development of CAD drawing. This step was undertaken in ANSYS Design modeler. The file was meshed with tetrahedral meshing scheme. Boundary conditions were applied in thermal analyses and then solution was performed. Step by step procedure is explain as follows,

3.7 Computer Aided Drawing (CAD)

1:1 scale of CAD model was developed as shown in Figure 3-8. Whereas the sectioned view of ICS is shown in Figure 3-9. It can be easily seen from figures that for fuel intake there is a square intake hatch. As per design of prototype, a grated bottom of first burning pit was created. There is a cylindrical pipe between first burning stove and secondary stove. This pipe then takes heated gases to the water cylinder and then they exit the ICS. Detailed view of main body of ICS has been shown in Figure 3-10. While sectioned view of water body is shown in Figure 3-11.

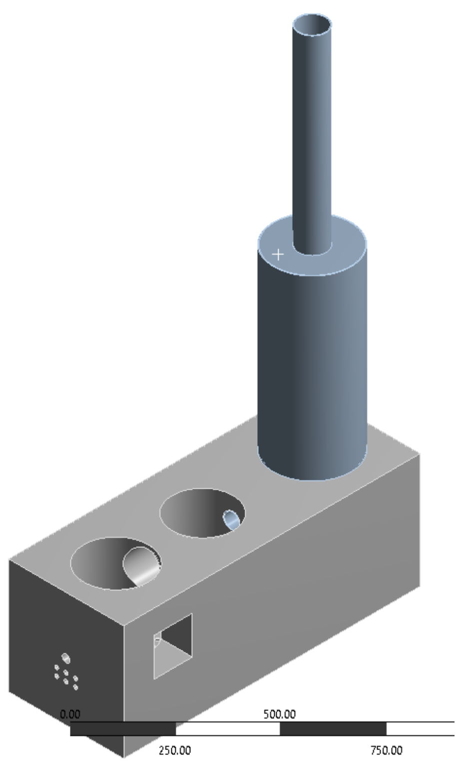

Figure 3- 8 Isometric view of CAD model

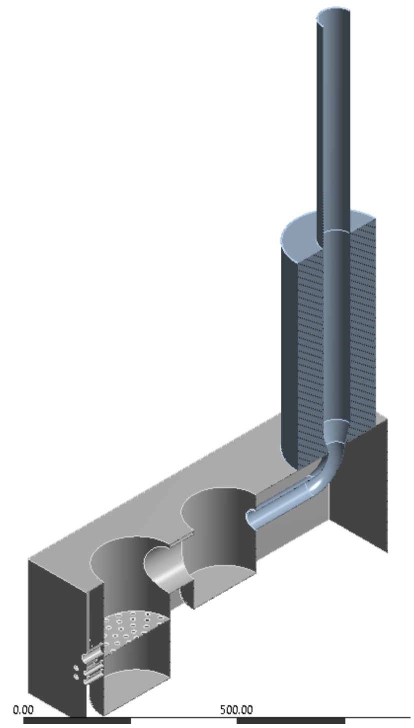

Figure 3- 9 Section view of complete ICS

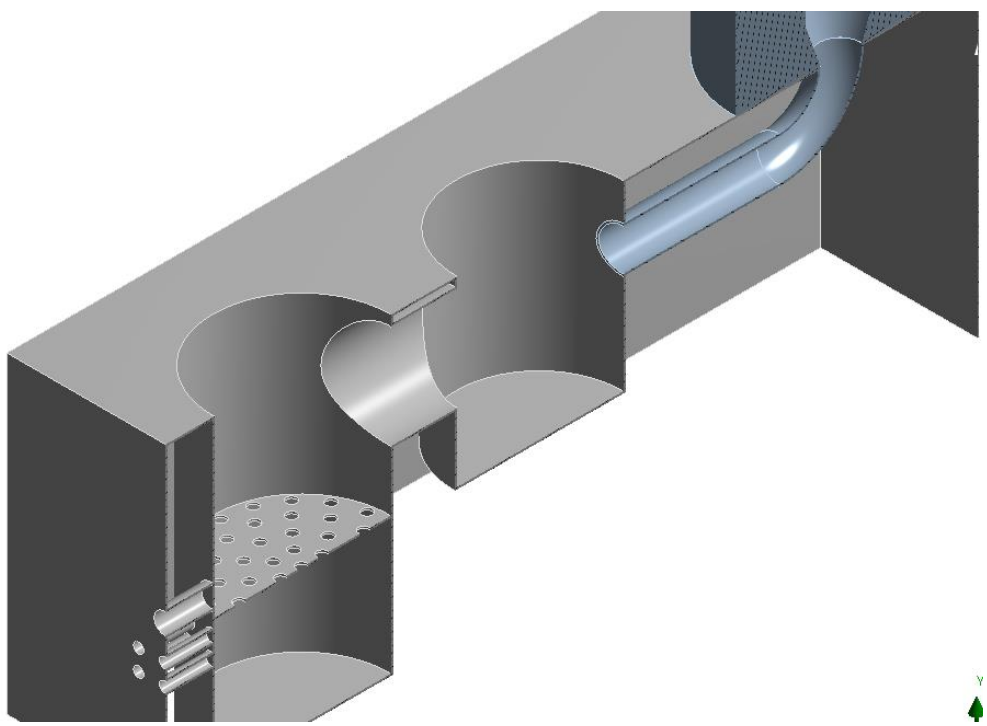

Figure 3- 10 Sectioned view of main body of ICS

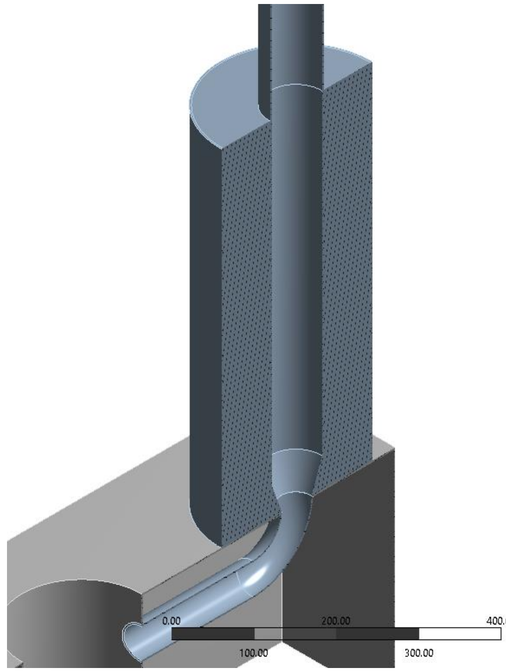

Figure 3- 11 Sectioned view of water body

3.8 Meshing of computational domain

In the 2nd step the CAD was loaded into ANSYS Mesh for meshing. ANSYS mesh is tool through which computational domain is discretized. The mesh is the physical representation of discretized domain. Discretized domain is a set of linked finite element on which governing equations are solved. The degree of freedom in thermal analysis is temperature, thus temperature is solved on all nodes of elements.

ICS has complex geometry. Geometry needs to be captured by mesh accurately as it can lead to wrong results. For meshing of complex geometries there are two options available Patch conforming tetrahedral methodology and Patch independent tetrahedral methodology.

3.8.1 Patch conforming tetrahedral methodology

ANSYS mesh uses the ANSYS T-Grid algorithms for meshing with patch conformal tetrahedral technique. Tetrahedral mesh originates from the outer geometry. Very complicated geometry can be modelled. Every geometric detail is recognized. This methodology can cope with very complex geometries but very small element can also be created. These elements can have large skewness values. Figure 3-12 shows the patch conformal methodology.

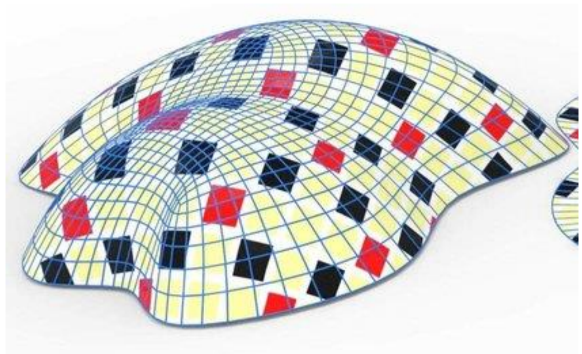

Figure 3- 12 Patch Conformal methodology

3.8.2 Path independent tetrahedral methodology

Patch independent methodology utilizes the same algorithms as ANSYS ICEM. Tetra mesh is originated from inside the desired mesh region. The mesh can walk over the regions depending upon a tolerance value. This effectively means that based on tolerance value, some reigns can simple be ignored. This is very useful when working with dirty cad geometries. However, high fidelity mesh can take a lot of effort.

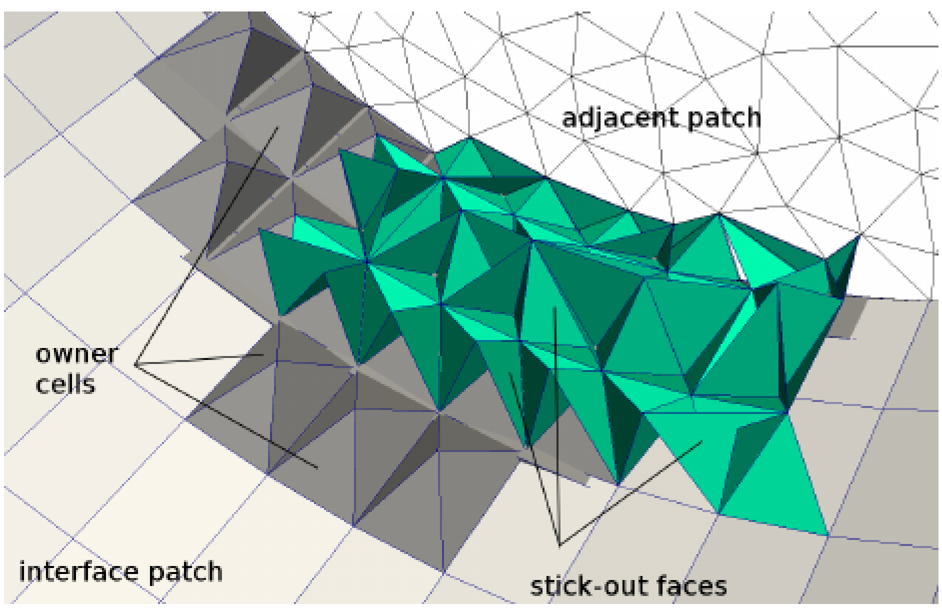

Figure 3- 13 Patch Independent tetrahedral mesh

The mesh of ICS can be seen from Figure 3-14 to Figure 3-16. The mesh is created using tetrahedral patch conformal mesh. The mesh size was used carefully, so that all features of the ICS were captured properly [51].

3.8.3 Governing Equations

A flame can be considered as the flow of a reacting gas mixture and, therefore, can be described by flow equations, which will model the fluid flow, and combustion equations. The flow equations described conservation of mass, momentum and energy equation.

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho U) = 0 \qquad (1)$$

Conservation of momentum:

$$\frac{\partial \rho U}{\partial t} + \nabla(\rho U \times U) = \nabla\big(-P + \mu(\nabla U + (\nabla U)T)\big) + SM \qquad (2)$$

By adding a source term in the conservation of momentum as shown in Equation (2), the full buoyancy model is accomplished.

The buoyancy force source term is a function of the local density variation.

$$S_{M,buoy} = (\rho - \rho_{ref})g \qquad (3)$$

Energy conservation:

$$\frac{\partial \rho h_{tot}}{\partial t} - \frac{\partial P}{\partial t} + +\nabla(\rho U h_{tot}) = \nabla(\lambda \nabla T) + SE \qquad (4)$$

Where h_{tot} is specific total enthalpy and it is defined as $h_{tot} = h + 1/2U^2$, where h = h(P, T). Moreover, dh is known as the change of enthalpy which can calculate in two steps: first, at constant a pressure equivalent to change of enthalpy for an ideal gas and then at constant a temperature. For the second step, a correction is required to real fluids. The total change in enthalpy is given by the following equation:

$$h_2 - h_1 = \int_{T_1}^{T_2} c_p dT + \int_{P_1}^{P_2} \left[\upsilon - T_2\left(\frac{\partial \upsilon}{\partial T}\right)\right] dP \qquad (5)$$

The k–ε flow model:

Two-equation turbulence model was used where two important terms k and ε are present. The momentum equation can be stated by the following equation:

$$\frac{\partial \rho U}{\partial t} + \nabla(\rho U \times U) - \nabla\left(\mu_{eff}\nabla U\right) = \nabla P' + \nabla\left(\mu_{eff}\nabla U\right)^{T} + B \qquad (6)$$

The Eddy break-up combustion model

During the combustion process, the energy released as heat that is estimated and the combustion rate of fuel is identified as a function of local flow properties. The dissipation rates of fuel, oxygen and products, and the slowest rate as the reaction rate of fuel are considered in the model. The following equation is used as transport equation for the mass fraction of fuel and this value is used.

$$R_{fu} = -\rho\left(\frac{\varepsilon}{k}\right)\min\left[C_R m_{fu}, C_R\left(\frac{m_{ox}}{s}\right), C'_R\left(\frac{m_{pr}}{1}+s\right)\right] \qquad (7)$$

The transport equation for mass fraction of fuel is

$$\frac{\partial(\rho m_{fu})}{\partial t} + \nabla\left(\rho m_{fu} U\right) = \nabla\left(r_{fu}\nabla m_{fu}\right) + R_{fu} \qquad (8)$$

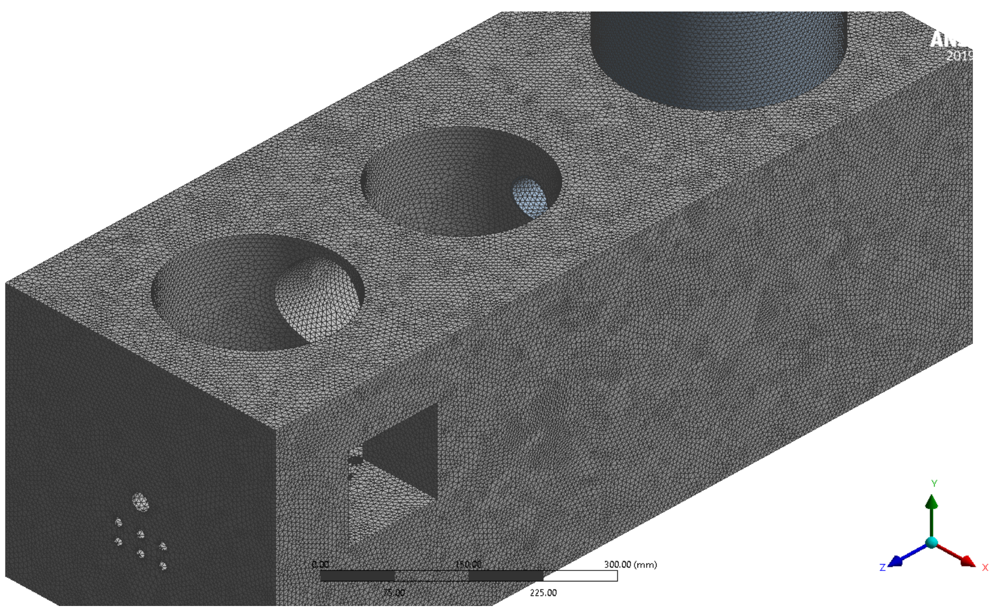

Figure 3- 14 Tetrahedral mesh of ICS

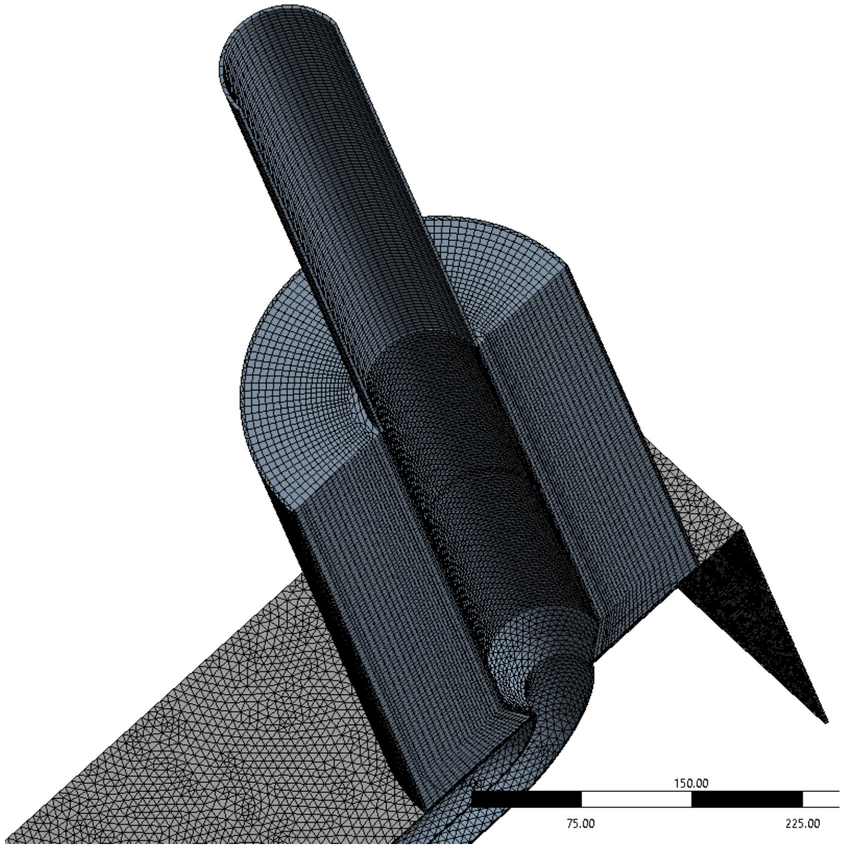

Figure 3- 15 Sectioned view of chimney and water body mesh

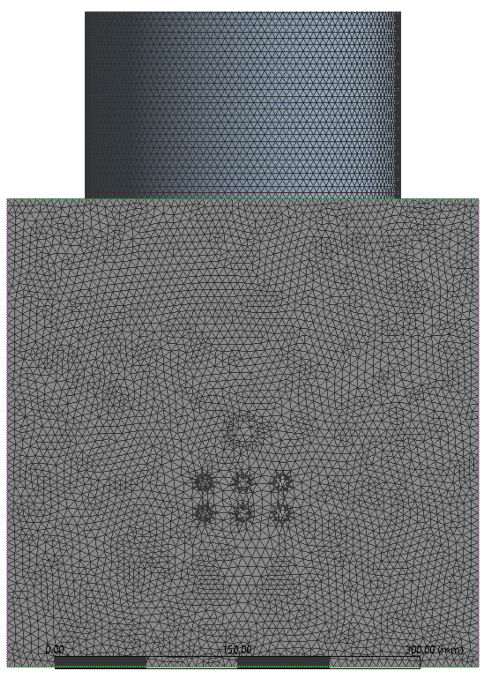

Figure 3- 16 Side view of mesh

3.9 Boundary Conditions

Thermal analysis of the computation domain was performed. Boundary conditions are given in Figure 3-17. The values of all temperatures were taken from experimental data. The analysis was performed for various conditions as given in Table 3-3.

Table 3- 3 Boundary conditions for thermal analysis

Sr #	Condition	Convective heat transfer coefficient
1	ICS inside a small closed kitchen, no air inlet in room	20 W/m^{2}K
2	ICS inside a larger room	50 W/m^{2}K
3	ICS inside a larger room with some convection air current	100 W/m^{2}K

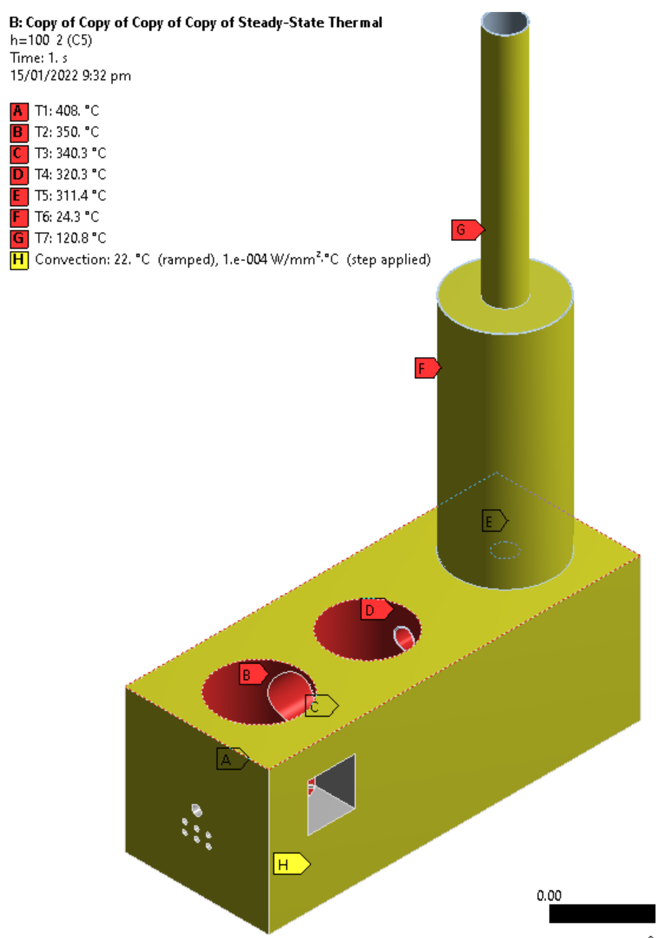

Figure 3- 17 Boundary Conditions for thermal analysis

A prototype was developed from literature review having primary and secondary stoves. The prototype was put through a detailed experimentation process and results of temperature were recorded. The experimentation was performed in a very control environment as fire hazards needs to be avoided. To simulate the rural working environment of ICS, thermal simulations were performed. Results obtained are by experimentation and simulation are discussed in the next chapter.

Summary

This chapter consists of the methodology that has been used to achieve the research objectives. Governing mechanism of heat transfer which is the basic and most important phenomena used in development of design of an ICS has been discussed in pursuance to the first law of thermodynamics. The heat transfer equations have been mentioned which are used in ICS to transfer heat through conduction, convection and radiation. Experimental verification of the ICS model has been described following the development of the ICS prototype. CAD drawings and models have been pasted showing the different views of designed ICS. A table of components has been added where material, which has been used for the construction of ICS prototype, along with the dimensions of each component has been listed down. Then the experimental setup is described where manufactured prototype is used for number of experiments and temperature has been recorded at 7 different points using thermocouples. Location of each thermocouple is also depicted using a model image. Thermal simulations is then described that a CAD model is designed again using ANSYS simulations software. Different components of thermal simulations including Computer aided drawings (CAD modeling), meshing of computational domains using patch conforming tetrahedral methodology, and boundary conditions used during simulations have been comprehensively and systematically described.

References

[1] NASA, United States, Accessed on 01 Jan, 2022, <https://www.grc.nasa.gov/www/k-12/airplane/thermo1.html>

[2] Lumen Physics, Accessed 01 Jan, 2022, <https://courses.lumenlearning.com/physics/chapter/14-4-heat-transfer-methods/>

[3] ANSYS Meshing user guide 2019, ANSYS Incorporation

CHAPTER 04

Results and Discussion

4.1 Experimental Results

As discussed earlier, the developed prototype was put through rigorous testing and experimentation. Thermocouple were attached at 7 places and after every 8 mins readings were noted manually. Results of experimentation are shown in Table 4-1. The graphical representation is shown in Figure 4-1. From the figure it can be seen that maximum combustion temperature of the main stove reaches up to 408.2 °C. This temperature is sufficient to prepare any kind of food. Minimum temperature of the smoke at outlet of chimney was measured 120.8 °C. The difference in the temperature clearly depicts that the thermal energy has been gained by the water body and loss to the environment. Thus raising the surrounding temperature. Maximum rise in temperature of water is 7 degrees. The water starts from 17.4^{o}C and after 56 mins reaches 24.2^{o}C with the corresponding flue gases temperature of 120.8^{o}C. This clearly indicates that more heat can be extracted from ICS by changing chimney design. But changing of chimney design will also increase cost of ICS.

The experimentation process is a complete multi-physics process. In order to keep it in safe limit, the Fuel was burned in a very control environment. Application of control environment and safety features deviates from actual working environment of Gilgit-Baltistan. Thus thermal simulations were performed with changing convective heat transfer to simulate the actual working condition of ICS.

Table 4- 1 Transient temperature variations during experimentation

Time (min)	T1	T2	T3	T4	T5	T6	T7
8	76.3	42.3	40.2	35.8	33.2	17.4	27.3
16	120.2	58.5	48.8	44.1	42.3	17.8	42.2
24	140.8	60.8	55.4	53.8	50.8	18.1	44.8
32	230.7	88.4	78.8	71.1	68.7	19.4	84.1
40	280.8	140.6	135.4	130.7	122.6	20.3	110.8
48	350.4	221.4	217.6	212.3	209.3	21.4	115.3
56	408.2	350.7	340.3	320.3	311.4	24.3	120.8

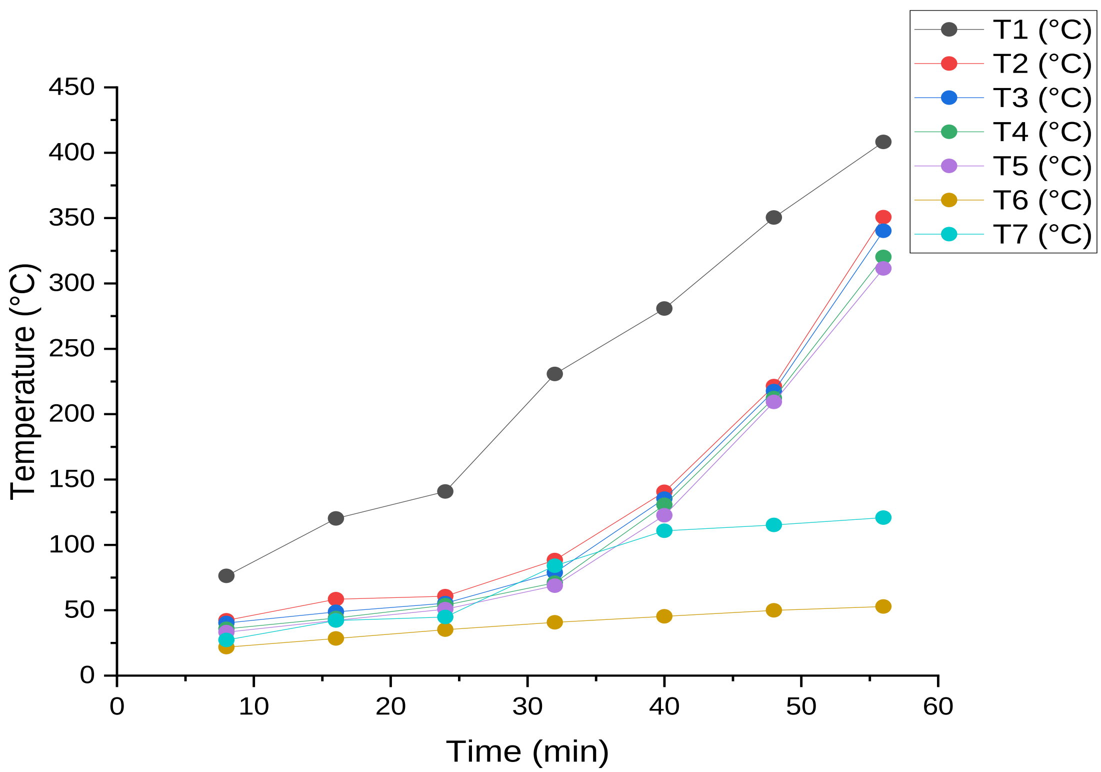

Figure 4- 1 Relative variation of temperature during experimentation

4.2 Numerical Results

The thermal simulations were performed using the experimental data as input boundary conditions. Convective heat transfer was varied from h=20 W/m^2K to 100 W/m^2K. As already discussed table 4-2 represents various considered design scenarios and their respective convective heat transfer coefficients.

4.2.1 ICS inside a small closed kitchen, no air inlet in room, h=20 W/m^2K

Results of thermal analysis of prototype ICS with h=20 W/m^2K is shown is shown from Figure 4-2 to Figure 4-7. Convective heat transfer coefficient of 20 W/m^2K represents a very small value. The small value of h means there are very little local convective heat transfer currents. The ICS has been placed in a very small kitchen with closed doors. Here the heat loss to environment depends solely on convection current between heated surface of ICS and surrounding wall.

Figure 4-2 shows the temperature contour of ICS. It can be seen that rise in temperature of outer wall of ICS is between 24^oC to 110^oC. This is significant rise in temperature as a surface of 100^oC can cause burns. Outer temperature of chimney can be seen from Figure 4-3. This section view clearly depicts the variation of temperature inside the ICS body. Surface temperature of ICS is shown in Figure 4-4. Maximum rise in temperature of surface for 20 W/m^2K is 350^oC.

Total heat flux contours are plotted from Figure 4-5 to Figure 4-7. Maximum value of total heat transfer is close to 5.1429 W/mm^2. The distribution of total heat flux through body can be seen from the sectioned Figure 4-6 and total heat flux distribution on ICS surface can be seen from Figure 4-7. Maximum value of heat flux on surface is 0.3616 W/mm2. That value is under the water tank thus depicting heat gain by gain. These values are low, thus indicating that a major chunk of heat is being thrown out of chimney and is being lost.

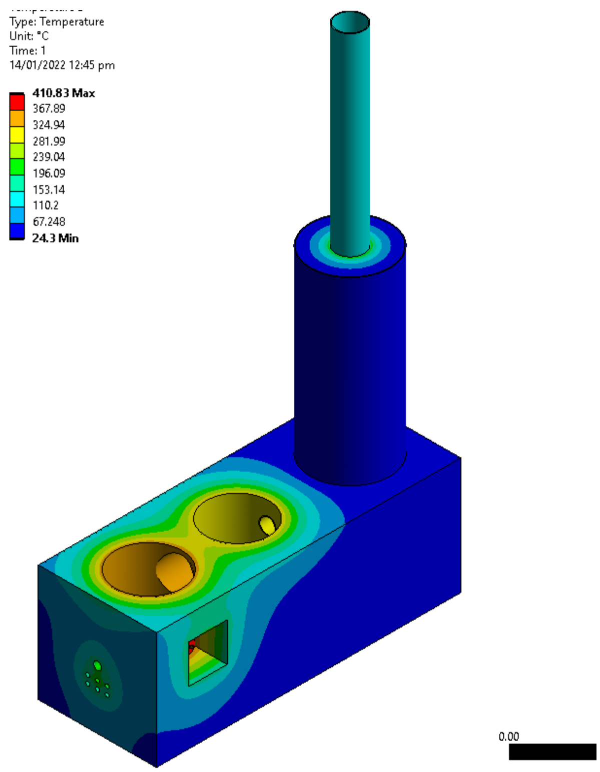

Figure 4- 2 Isometric temperature contour for h=20 w/m2K

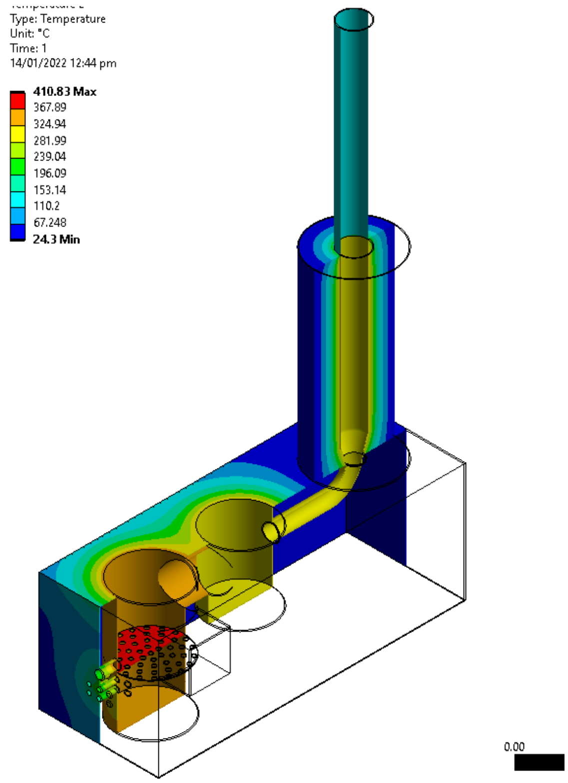

Figure 4- 3 Isometric sectioned temperature contour for h=20 w/m2K

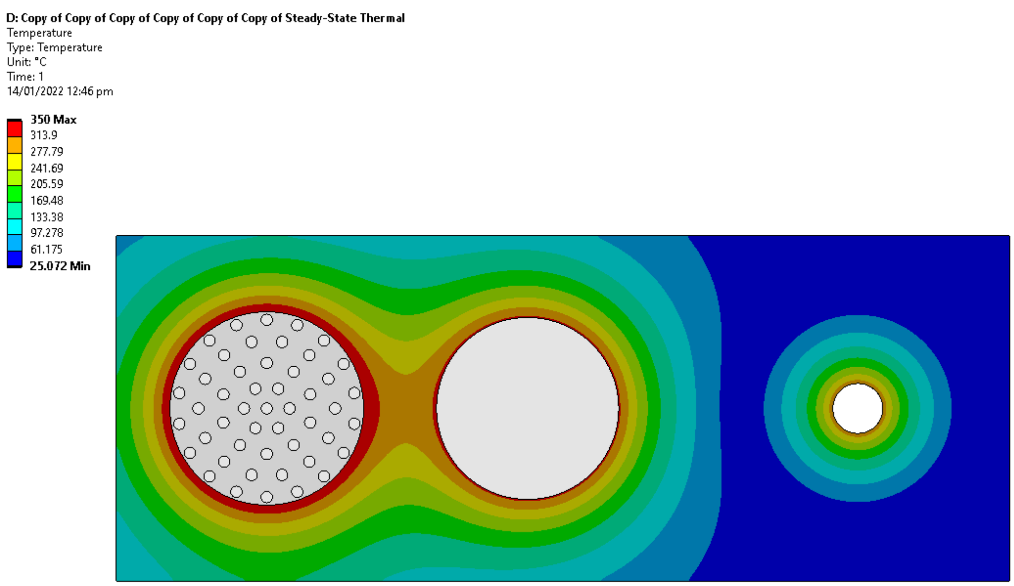

Figure 4- 4 Temperature contour at ICS surface for h=20 W/m2K

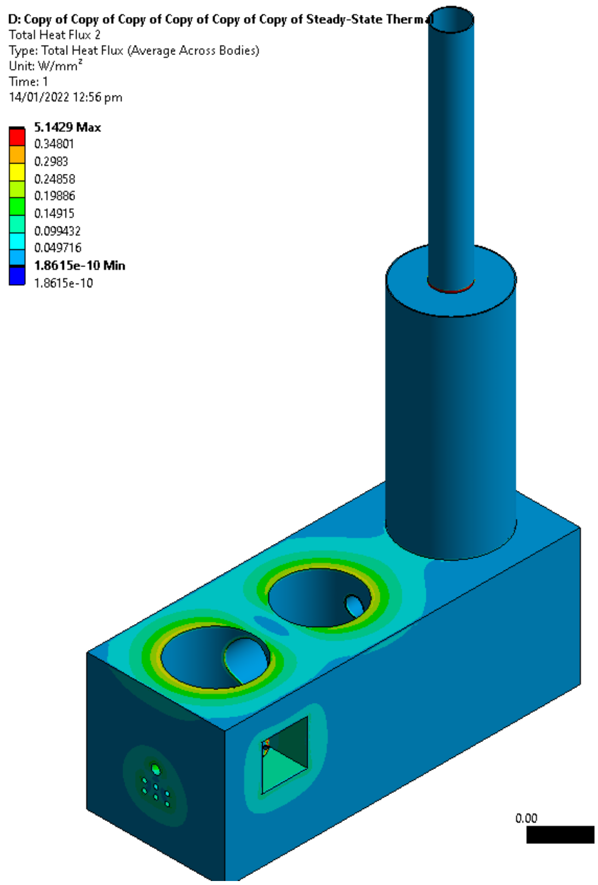

Figure 4- 5 Total Heat flux for h=20 W/m2K

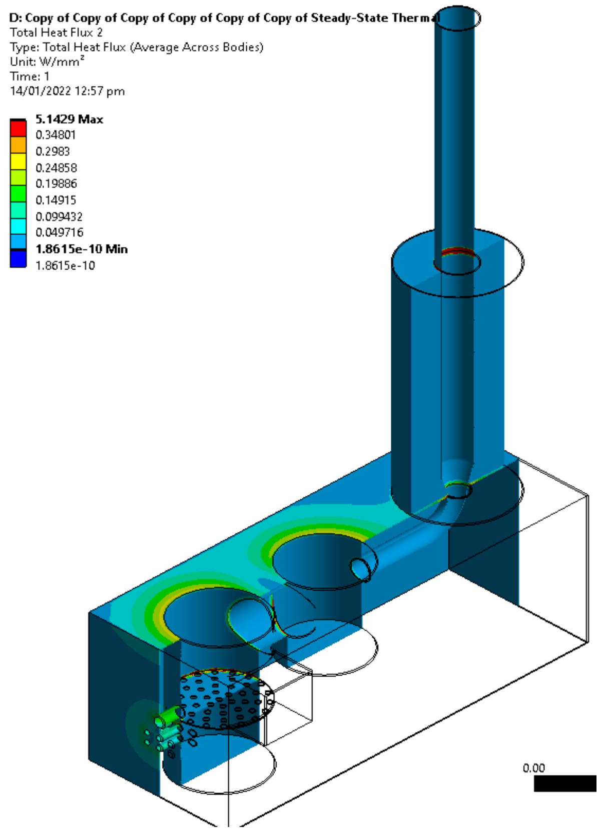

Figure 4- 6 Sectioned view of total heat flux for h=20 W/m2K

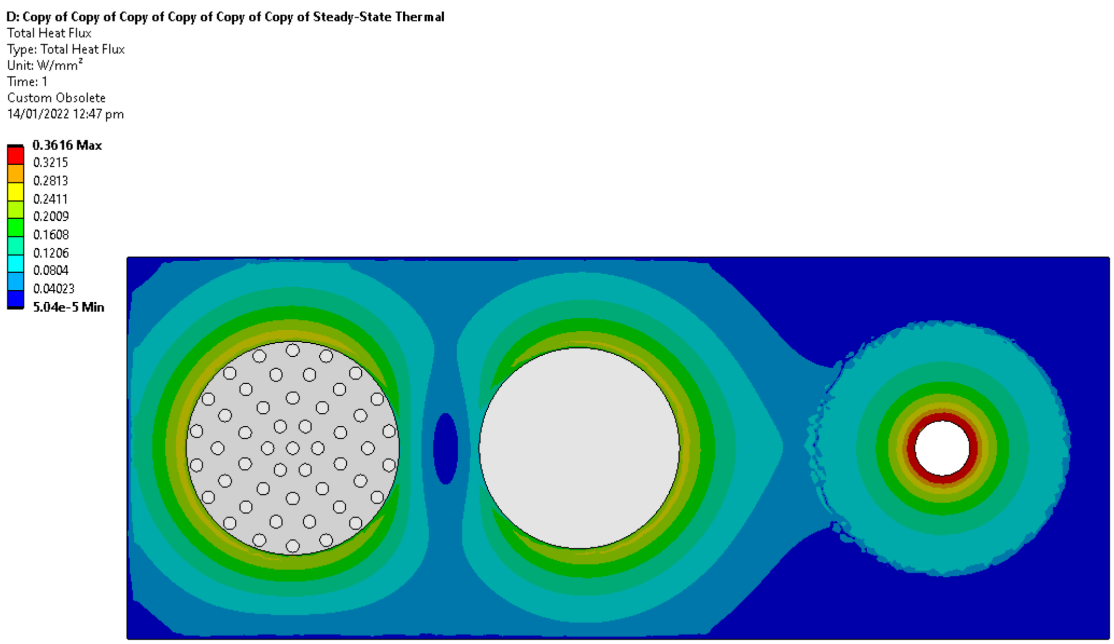

Figure 4- 7 Total Heat flux at ICS surface for h=20 W/m2K

4.2.2 ICS inside a larger room, h=50 W/m^{2}K

The second case scenario represents when ICS is placed in a bigger kitchen. The kitchen has better air circulation between ICS surface and surrounding walls. Thus heat transfer from ICS to the room is better. For this design scenario, convective heat transfer coefficient has been taken as 50 W/m^{2}K. Figure 4-8 to Figure 4-13 represents the results of this simulation.

Temperature contour of entire ICS for convective heat transfer coefficient of 50 W/m^{2}K is shown in Figure 4-8. It can be seen from figure that side surface temperature rise is between 65^{o}C to 108^{o}C. Maximum surface is at 22^{o}C. Same effect can be seen in Figure 4-9. The sectioned view clearly shows the temperature of water body. The rise in temperature is a bit less than previous convective case as more heat is lost to environment. The upper surface rise in temperature is shown in Figure 4-10. The Maximum rise in temperature is same as previous cases, as convective surfaces are a bit further apart. But the effect of water body is more on the surface.

Figure 4-11 shows the total heat flux contour for entire convective surface. It can be seen that maximum value of total heat flux is 6.176 W/mm^2. The heat flux distribution can be seen from sectioned Figure 4-12. Dominant blue region is indicative of more heat loss to environment. Figure 4-13 shows the upper surface heat flux distribution.

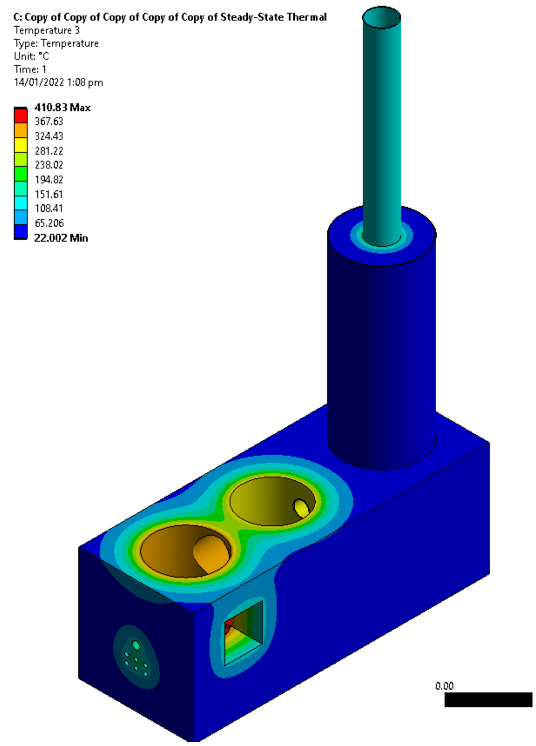

Figure 4- 8 Isometric temperature contour for h=50 w/m2K

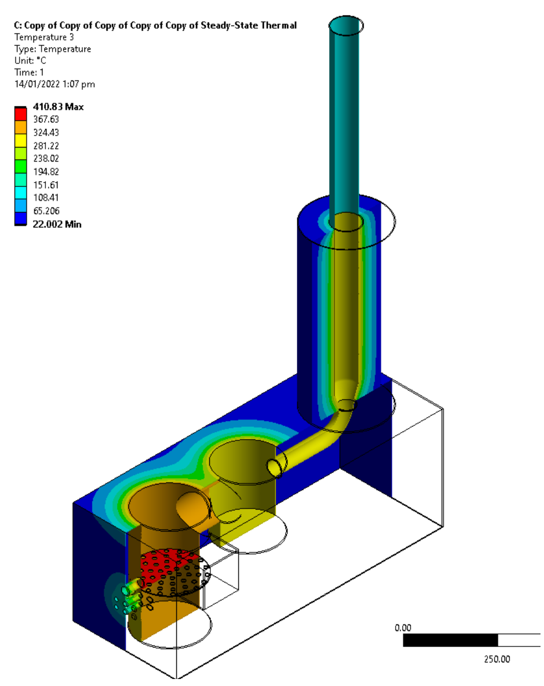

Figure 4- 9 Isometric sectioned temperature contour for h=50 w/m2K

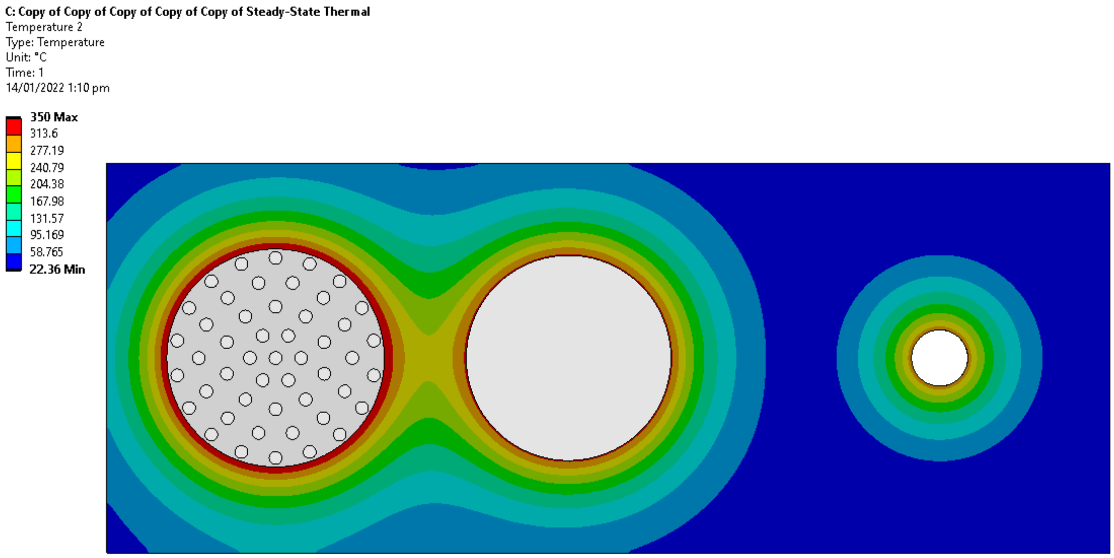

Figure 4- 10 Temperature contour at ICS surface for h=50 W/m2K

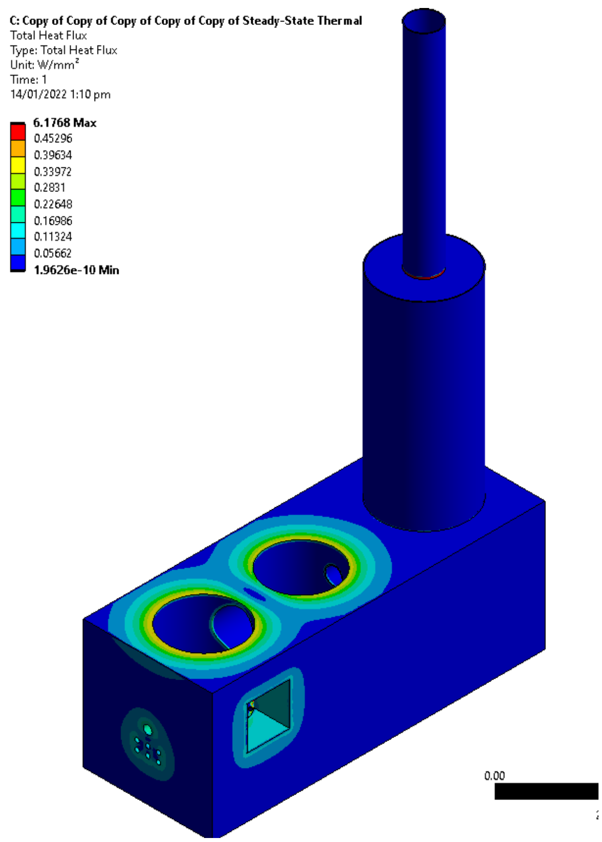

Figure 4- 11 Total heat flux for h=50 W/m2K

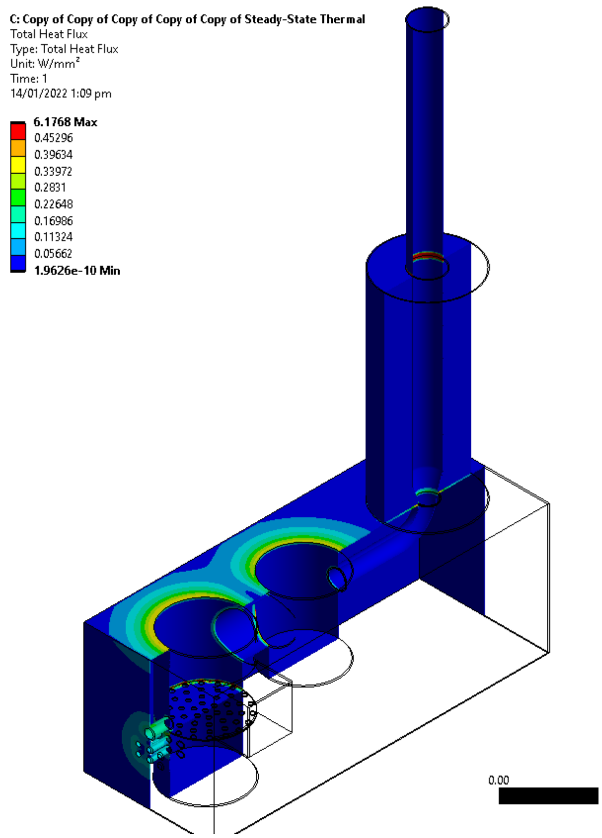

Figure 4- 12 Sectioned view of total heat flux for h=50 W/m2K

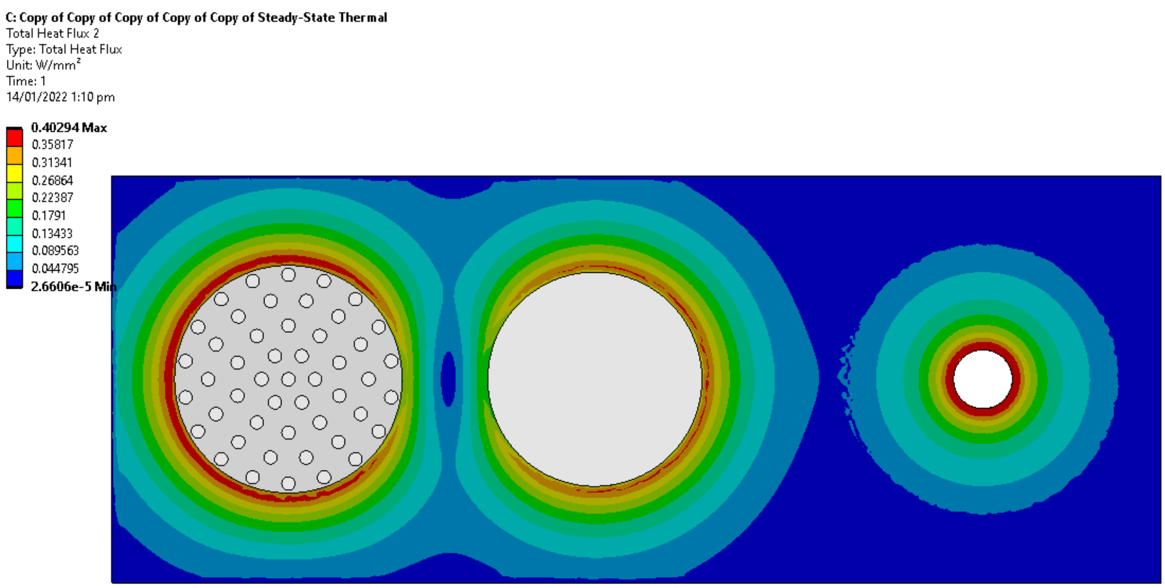

Figure 4- 13 Total Heat flux at ICS surface for h=50 W/m2K

4.2.3 ICS inside a larger room with some convection air current, h=100 W/m^2K

The third case is when the ICS has been placed in a place having better convective heat transfer coefficient. Heat transfer from ICS is better due outer surface air currents. Although the value of 100 W/m^2K is still very conservative but it is better than previous cases. Figure 4-14 to Figure 4-19 shows the details of thermal simulations performed for a convective heat transfer of 100 W/m^2K.

Figure 4-14 shows the temperature contour on entire ICS surface. It can be seen from figure that maximum rise in on side surface is close to 62^oC. This rise is temperature is a clear indication of better heat transfer from surface as the source remains the same for all simulations. The sectioned view as shown in Figure 4-15 is also an indication of better heat transfer. Figure 4-16 shows the maximum rise in temperature of top of surface is same as previous but its distributions much more conservative.

Total heat flux for a convective heat transfer coefficient of 100 W/m^2K is shown in Figure 4-17. While its section view is shown in Figure 4-18. The maximum value of total heat flux is 6.17 W/mm^2. Same conservative heat flux trend is obvious on the top surface of ICS as shown in Figure 4-19.

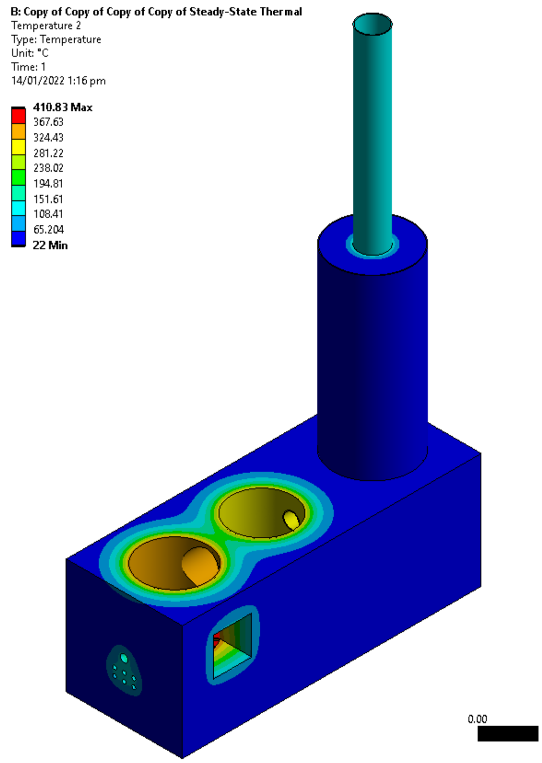

Figure 4- 14 Isometric temperature contour for h=100 w/m2K

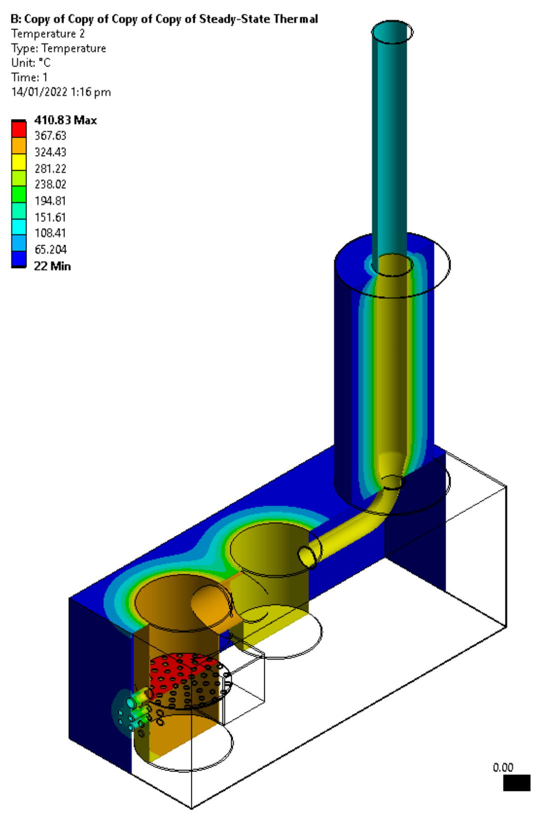

Figure 4- 15 Isometric sectioned temperature contour for h=100 w/m2K

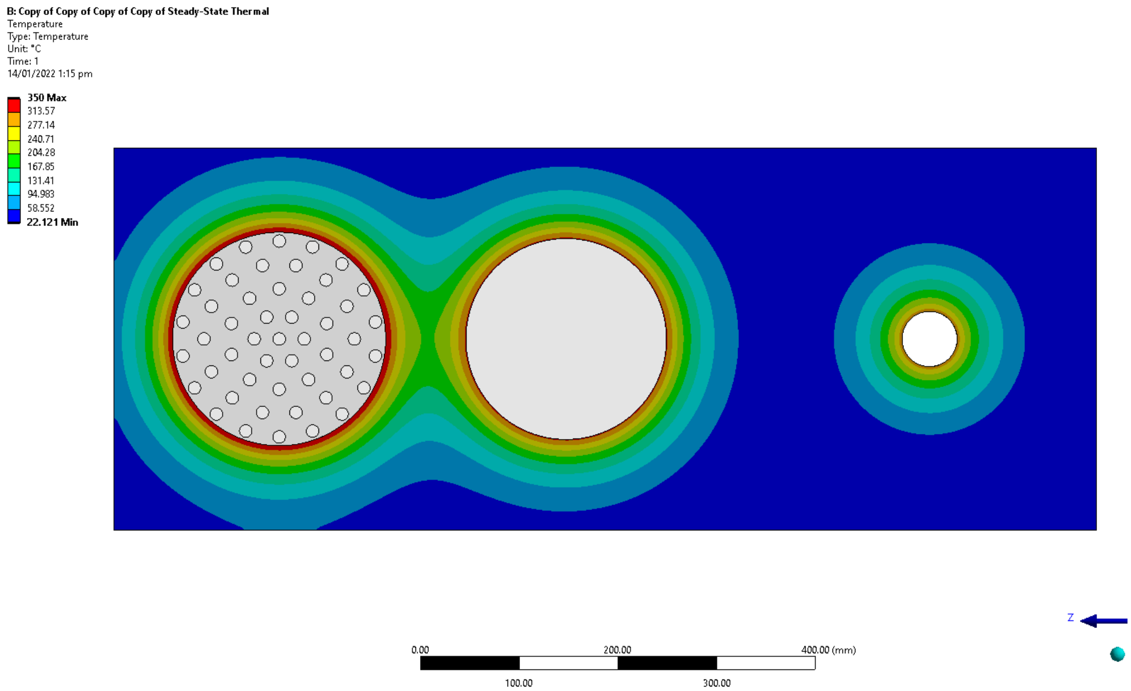

Figure 4- 16 Temperature contour at ICS surface for h=100 W/m2K

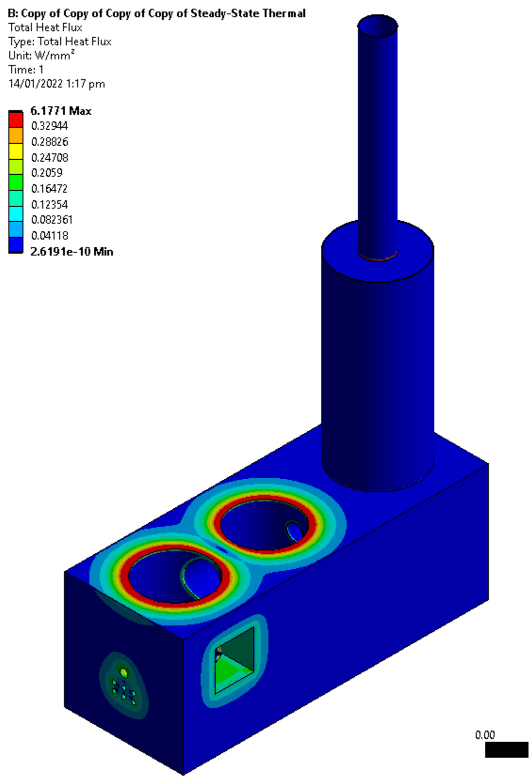

Figure 4- 17 Total heat flux for h=100 W/m2K

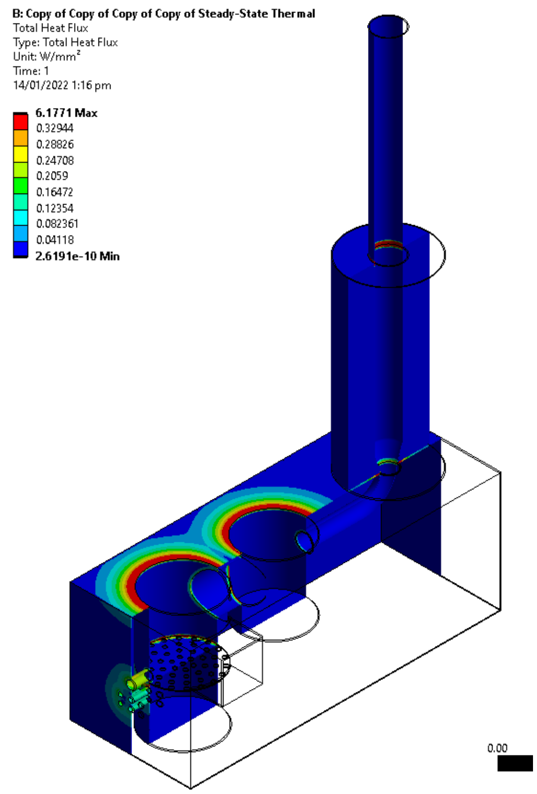

Figure 4- 18 Sectioned view of total heat flux for h=100 W/m2K

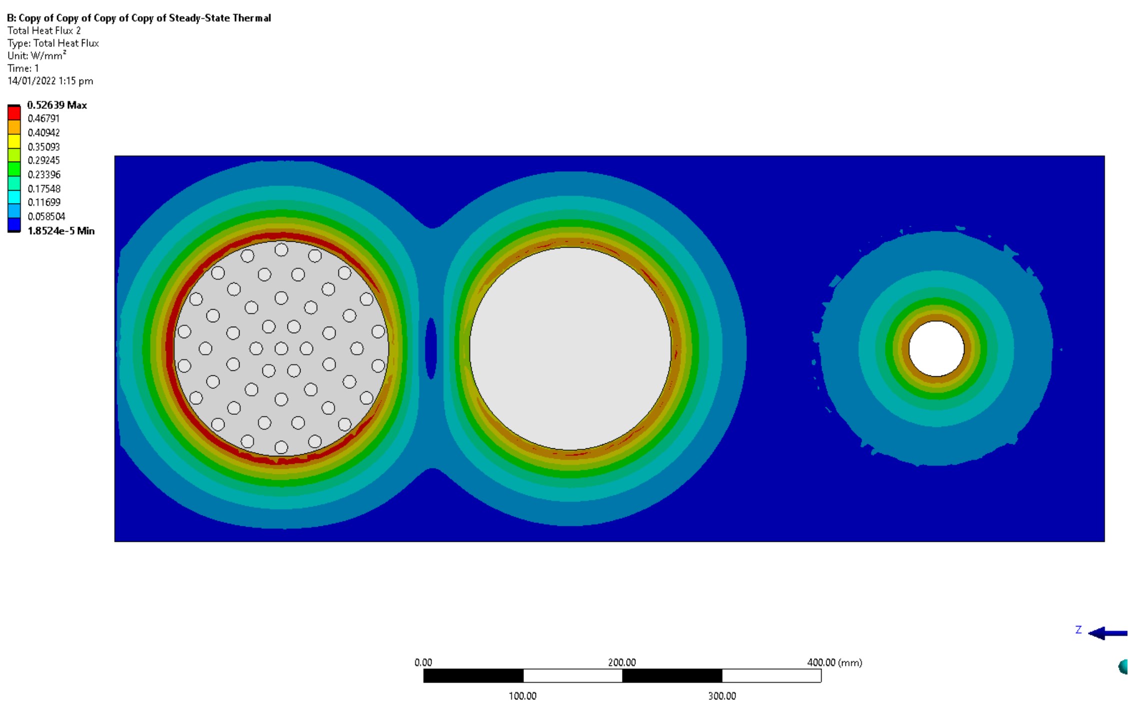

Figure 4- 19 Total Heat flux at ICS surface for h=100 W/m2K

4.3 Performance Analysis

The results from the thermal simulation and experiments are used to find the performance of the proposed ICS model.

4.3.1 Burn rate (FCR) kg/hr: This is the fuel consumed in the stove by the total operational time. The formula is used to calculate this;

$$\boldsymbol{Burn\ Rate = \frac{Weight\ of\ fuel\ consumed, kg}{Operating\ time, hr}}$$

4.3.2 Thermal Efficiency (n_{th}): This is the ratio of work done by heating and evaporating water to the energy consumed by burning wood. The formula is used to calculate this;

$$n_{th} = \frac{c_{p,water} \times (P_{ci} - P) \times (T_{cf} - T_{ci}) + HV_{water} \times (w_{cv})}{f_{cd} \times LHV}$$

Where,

$C_{p,water}$ = Specific heat of water (J/g.K)
P_{ci} = Weight of Pot with water before test (g)
P = Dry weight of empty Pot (g)
T_{cf} = Water temperature after test (ºC)
T_{ci} = Water temperature before test (ºC)
HV_{water} = Calorific value of water (J/g)
w_{cv} = Water vaporized (g)
f_{cd} = Equivalent dry wood consumed (g)
LHV = Net calorific value (dry wood) (MJ/kg)

4.3.3 Power output: This is the sum of energy that the stove releases to cook. The formula is determined,

$$P_o = FCR \times HV_f \times T_E$$

Where:

P_o = Power output, (kW)

FCR = Fuel consumption rate, (kg/hr.)

HV_f = Calorific value of fuel (dry wood) (kJ/kg)

T_E = Thermal efficiency, (%)

4.4 Comparison of proposed ICS model with other stoves

	Proposed ICS Prototype	Traditional Cooking Stove	Bukhari Stove	Cooking Stove MA-IV	ICS Model SAARC-II
Functions	1. Smoke less 2. Cooking, Baking, 3. Meal heating 4. Water heating, 5. Space heating, 6. Oven, 7. Controlled Burning Rate (Low Power, High Power)	1. Cooking only	1. Smoke less 2. Cooking 3. Meal heating 4. Space heating	5. Smoke less 6. Cooking or baking (one function at a time)	7. Smoke less 8. Cooking 9. Space heating 10. Controlled Burning Rate (Low Power, High Power)
Body Type	Metal Body	Mud or Clay	Metal Body	Mud or Clay	Metal Body
Burning rate	20.22 g/min	N/A	N/A	N/A	15.84 g/min
Fire Power	8.39 kW	N/A	N/A	N/A	4.93 KW
Thermal Efficiency	38.60 %	8-12%	15-22 %	N/A	46.6%
Heat Trapping	Yes, through sealed body with insulation	No	No	NO	Yes, through insulation
Portability	Portable	Fix	Portable	Fix	Portable

Summary

This chapter consists of experimental results which have been concluded as the prototype that was created was put through extensive testing and experimentation. Thermocouples were installed in 7 locations, and measurements were taken manually every eight minutes. The primary stove's maximum combustion temperature is 408.2 degrees Celsius. The temperature of the water may increase to a maximum of 7 degrees. The water temperature starts at 17.4 degrees Celsius and rises to 24.2 degrees Celsius after 56 minutes, with a flue gas temperature of 120.8 degrees Celsius. This clearly shows that modifying the chimney design may extract more heat from ICS. Any type of food may be prepared at this temperature. However, modifying the chimney design will raise the cost of ICS.

The experimental data were used as input boundary conditions for the thermal simulations. From h=20 W/m^2K to 100 W/m^2K, convective heat transmission was varied. Thermal study of a prototype ICS with h=20 W/m^2K to 100 W/m^2K results are given. Surface temperatures of the ICS are depicted in several figures, as well as the overall heat flux distribution on the ICS surface. The maximum overall heat transfer value in case of h=20 W/m^2K is close to 5.1429 W/mm^2. This is a substantial temperature increase, since a surface temperature of 100^oC can inflict burns. The overall heat flux profile for the full convective surface of ICS is shown in Figure 4-7.

The heat flux pattern for a convective heat transfer of 100 W/m^2K is shown in Figure 4-14. The temperature contour for the whole ICS surface is shown in Figure 4-19. The highest temperature rise on the side surface is close to 62^oC. Because the source remains constant across all simulations, this increase in temperature is a clear sign of improved heat transfer from the surface.

Chapter 5

Conclusions and Recommendations

6.1 Conclusions

A study was performed for design, fabrication and analysis of ICS. For this purpose, design of a prototype ICS was conceived and manufactured. The prototype was tested/experimented. The experimental conditions were not actual depiction of ICS operating conditions so thermal simulations were performed to ensure its operations in actual design conditions. Following conclusions can be drawn from the study,

i. An improved cooking stove (ICS) is design which helps in efficient and effective combustion of biomass fuels for cold rural populations.
ii. The proposed design also significantly increase fuel savings and minimize hazardous gases emissions.
iii. As experimental conditions were not actual depiction of ICS operating conditions so thermal simulations were also performed for the validation of results to ensure its performance.
iv. While for the areas at high altitude and cold weather, metal body of proposed ICS prototype is use for multiple purposes including cooking and space heating.
v. Maximum temperature reached up to 410.83°C.
vi. Thermal efficiency of the stove is found to be 38.60%.
vii. Burning rate of fuel is calculated to be 20.22 g/min.
viii. The ICS can produce a firepower of 8.39 kW.
ix. Fuel saving is found to be 68% as compare to ancestors ICS models.

6.2 Recommendations

On the basis of study, it is recommended that more experimentation should be performed with prototype ICS by incorporating design changes for better utilization of flue gases energy. It is also recommended that for better understanding of life prediction of ICS, complete multi-physics analysis involving thermal, hydraulic and stresses may be performed.

Appendix

Performance Investigation of novel Improved Cooking Stove Model for cold rural population

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Abstract:

In Pakistan 50.8% of the total population use traditional methods to cook by burning wood, animal manure and agricultural residue causing enormous greenhouse gases emissions. A new type improved cooking stove (ICS) for complete combustion of biomass fuel to decrease hazardous gas emissions, improving overall efficiency, and lowering fuel consumption is proposed in the current studies for rural populations. Numerical simulations are performed using ANSYS to show heat transfer analysis of the proposed design. The performance evaluation Tests of the prototype i.e., roti making test, water boiling test and flame test; and the numerical analysis show that thermal efficiency, fuel saving, burning rate and fire power durability are promising. Conclusively, proposed ICS can help the communities of developing countries to make their life better in terms of good indoor air quality and better health.

Keywords: Improved cooking stove (ICS); Household Air Pollution; Particulate Matters; Thermal Efficiency; Combustion Efficiency.

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