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Original Research Paper

Computational Fluid Dynamics Investigation and Thermal Performance Optimisation of a Domestic Biogas Cookstove Burner: Influence of Burner Port Diameter on Flame Characteristics and Energy Efficiency

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Abstract

The growing demand for sustainable household energy systems has intensified interest in biogas as a renewable substitute for conventional cooking fuels such as liquefied petroleum gas (LPG) and piped natural gas (PNG). Although biogas cookstoves have been widely adopted in rural and semi-urban communities, their thermal performance remains highly dependent on burner geometry and combustion characteristics. This study presents a computational fluid dynamics (CFD) investigation of a domestic biogas cookstove burner to evaluate the influence of burner port diameter on flame structure, temperature distribution, heat transfer behaviour, and thermal efficiency. Four burner port diameters (3.5, 4.0, 4.5, and 5.0 mm) were examined under identical operating conditions, including a fuel flow rate of 4 L min^{-1}, injector diameter of 2.5 mm, loading height of 25 mm, and a standard cooking vessel with an external diameter of 180 mm and height of 100 mm. Numerical simulations were conducted using ANSYS Fluent with the standard k–ε turbulence model, species transport formulation, discrete ordinates radiation model, and a two-step methane combustion mechanism representing biogas containing 48.5% CH_4 and 51.5% CO_2. Performance evaluation followed the water-boiling test procedure specified in Indian Standard IS 8749:2002. Results indicate that maximum flame temperatures occur near burner ports and reach approximately 2400 K before decreasing due to heat transfer and buoyancy-induced flow expansion. The vessel bottom exhibits a dual-peak temperature distribution, with major heat transfer zones located directly above the burner and within the radial distance of 50–80 mm from the burner centre. Burner port diameters of 4.0 mm and 4.5 mm produced comparable thermal behaviour, whereas the 5.0 mm configuration resulted in reduced average temperatures and lower heat transfer rates. The highest thermal efficiency of 61.64% was obtained with the 4.0 mm burner port diameter. The findings demonstrate that burner port diameter moderately influences combustion performance and that optimised port geometry can enhance energy utilisation without increasing fuel consumption. The study contributes to the development of high-efficiency, low-cost biogas cookstoves for sustainable household energy applications.

Keywords: biogas combustion, cookstove burner, Computational fluid dynamics, thermal efficiency, renewable energy, heat transfer, burner optimization

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INTRODUCTION

1.1 Background of the Study

Global energy demand continues to increase due to population growth, urbanisation, and industrial development. Household cooking accounts for a significant proportion of energy consumption, particularly in developing countries where biomass fuels remain dominant. Traditional cooking practices often result in low thermal efficiency, excessive fuel consumption, and adverse environmental impacts.

Biogas has emerged as a promising renewable energy source because it is produced through anaerobic digestion of organic waste materials and can be utilised directly for cooking and heating applications. Unlike conventional fossil fuels, biogas offers advantages including carbon neutrality, waste management benefits, and reduced greenhouse gas emissions. Recent investigations have demonstrated that optimised biogas cookstoves can achieve thermal efficiencies exceeding 50%, making them viable alternatives to LPG and biomass-based cooking systems.

Despite these advantages, the efficiency of biogas cookstoves depends strongly on burner design parameters such as injector size, mixing tube dimensions, air-fuel ratio, flame port geometry, and vessel loading height. Among these parameters, burner port diameter plays a critical role in controlling flame stability, combustion intensity, and heat transfer to the cooking vessel.

Computational Fluid Dynamics (CFD) provides a cost-effective approach for investigating combustion phenomena and optimising burner geometries. CFD enables visualisation of velocity fields, species concentration distributions, temperature gradients, and heat transfer mechanisms that are difficult to obtain experimentally. Previous studies have shown that CFD-based optimisation can significantly improve thermal efficiency and reduce fuel consumption in domestic burners.

1.2 Statement of the Problem

Although biogas cookstoves have been extensively deployed, there remains limited understanding of how burner port diameter affects flame behaviour and thermal efficiency under standardised operating conditions. Many existing cookstoves are designed using empirical approaches that may not maximise energy utilisation.

The lack of optimised burner configurations leads to:

- Reduced thermal efficiency;
- Increased fuel consumption;
- Flame instability;
- Higher heat losses;
- Lower cooking performance.

A numerical investigation is therefore required to establish the relationship between burner port diameter and combustion characteristics.

1.3 Aim and Objectives

Aim

To investigate numerically the effect of burner port diameter on the thermal performance of a domestic biogas cookstove burner.

Objectives

1. To develop a CFD model of a domestic biogas cookstove burner.
2. To evaluate flame temperature distributions for different burner port diameters.
3. To analyse heat transfer characteristics between flame and vessel.
4. To determine thermal efficiency under standardised operating conditions.
5. To identify the optimum burner port diameter for enhanced performance.

1.4 Research Questions

1. How does burner port diameter influence flame temperature?
2. What is the relationship between burner port diameter and heat transfer rate?
3. Which burner port diameter yields maximum thermal efficiency?

1.5 Significance of the Study

The study contributes to:

- Sustainable household energy development;
- Improved biogas utilisation;
- Reduced dependence on fossil fuels;
- Enhanced cookstove design methodologies;
- Advancement of CFD applications in renewable energy systems.

1.6 Scope of the Study

The investigation considers:

- Burner port diameters of 3.5, 4.0, 4.5, and 5.0 mm;
- Biogas composition of 48.5% CH_4 and 51.5% CO_2;
- Constant fuel flow rate of 4 LPM;
- Water boiling test conditions according to IS 8749:2002.

LITERATURE REVIEW

2.1 Biogas as a Renewable Cooking Fuel

Biogas is a renewable gaseous fuel generated through the anaerobic digestion of organic materials such as agricultural residues, animal manure, municipal solid waste, and sewage sludge. Its composition typically consists of 50–70% methane (CH_4), 30–50% carbon dioxide (CO_2), and trace quantities of hydrogen sulphide, nitrogen, and water vapour. The energy content of biogas is primarily determined by its methane concentration, with reported calorific values ranging from approximately 18 to 25 MJ/m³ (Kaczmarczyk & Włodarczak, 2021). Due to its renewable nature and ability to convert organic waste into useful energy, biogas has become an important component of sustainable energy strategies, particularly in rural and off-grid communities.

The use of biogas for domestic cooking offers several environmental and socio-economic advantages. It reduces dependence on traditional biomass fuels such as firewood and charcoal, thereby mitigating deforestation and indoor air pollution. In addition, biogas systems contribute to greenhouse gas mitigation by capturing methane that would otherwise be released into the atmosphere from decomposing organic waste. Consequently, biogas is widely recognised as a clean, affordable, and sustainable cooking fuel that supports both energy security and environmental protection.

2.2 Combustion Characteristics of Biogas

The combustion behaviour of biogas differs significantly from that of pure methane because of the substantial proportion of carbon dioxide present in the fuel mixture. Carbon dioxide acts as an inert diluent that absorbs heat during combustion and lowers the concentration of reactive species within the flame. As a result, increasing CO_2 concentration reduces laminar flame speed, narrows the flammability limits, and decreases flame stability (Taştan et al., 2014; Tutak et al., 2021). These effects can lead to difficulties in maintaining stable combustion under certain operating conditions.

Furthermore, the presence of CO_2 lowers the adiabatic flame temperature by increasing the heat capacity of the reactant mixture and reducing the overall heating value of the fuel. Numerical and experimental investigations have shown that higher carbon dioxide concentrations significantly suppress flame propagation and reduce combustion intensity through both thermal and dilution mechanisms (Wang et al., 2021). Consequently, burner designs intended for biogas applications must account for the reduced reactivity and lower flame temperatures associated with high CO_2 content to achieve efficient and stable operation.

2.3 Domestic Biogas Cookstoves

Domestic biogas cookstoves are specifically designed to accommodate the unique combustion characteristics of biogas while maximising thermal efficiency and minimising pollutant emissions. Conventional atmospheric biogas burners generally achieve thermal efficiencies ranging from approximately 46% to 54%, depending on burner geometry, fuel composition, and operating conditions (Kumar et al., 2025). Although these burners are simple and inexpensive, incomplete fuel-air mixing and heat losses often limit their performance.

To overcome these limitations, researchers have developed advanced burner configurations, including porous radiant burners and porous media combustion systems. These technologies enhance combustion by promoting better fuel-air mixing, increasing residence time, and improving heat recirculation within the combustion zone. Studies have reported thermal efficiencies exceeding 59% for porous radiant burner designs, with some optimised systems achieving efficiencies above 70% under controlled laboratory conditions (Kumar et al., 2025). In addition to improved efficiency, porous burner systems have demonstrated lower carbon monoxide and nitrogen oxide emissions, making them attractive alternatives for sustainable domestic cooking applications.

2.4 Computational Fluid Dynamics Applications in Cookstove Design

Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analysing combustion processes and improving the design of domestic cooking appliances. CFD enables researchers to simulate complex interactions among fluid flow, heat transfer, chemical reactions, and species transport within combustion systems. Compared with purely experimental approaches, CFD provides detailed information about temperature distributions, velocity fields, turbulence characteristics, and pollutant formation mechanisms that are often difficult or expensive to measure directly.

In cookstove research, CFD has been widely applied to investigate burner performance, optimise fuel-air mixing, evaluate thermal efficiency, and reduce emissions. Common modelling approaches include Reynolds-Averaged Navier–Stokes (RANS) turbulence models, species transport models, combustion reaction mechanisms, and radiation heat transfer models. These techniques allow researchers to predict flame behaviour and assess the influence of design modifications before constructing physical prototypes. As a result, CFD has become an essential design and optimisation tool for modern biogas combustion systems.

2.5 Influence of Burner Port Geometry on Performance

Burner port geometry is one of the most important design parameters affecting the performance of domestic biogas cookstoves. The diameter, shape, and arrangement of burner ports directly influence fuel-air mixing, flame stability, jet velocity, combustion efficiency, and heat transfer to the cooking vessel.

Port diameter determines the velocity at which the fuel-air mixture exits the burner. Smaller ports generally produce higher jet velocities, which can enhance mixing but may also increase the risk of flame lift-off if velocities exceed flame propagation rates. Conversely, larger ports tend to reduce jet velocity and may promote flame instability or incomplete combustion due to poorer mixing. The geometry of burner ports also affects flame anchoring and temperature distribution across the burner surface, thereby influencing overall thermal performance.

Previous studies have demonstrated that appropriately sized burner ports can significantly improve combustion efficiency and heat transfer effectiveness. Optimisation of burner port dimensions has been shown to enhance flame stability while reducing heat loss, leading to improved thermal efficiency and lower emissions. Therefore, burner port geometry remains a critical design variable in the development of high-performance biogas cookstoves.

2.6 Research Gap

Despite considerable progress in biogas cookstove development, existing research has predominantly focused on the experimental optimisation of burner configurations and the application of porous media combustion technologies. While these studies have demonstrated significant improvements in thermal efficiency and emission performance, relatively few investigations have systematically examined the influence of burner port diameter using advanced numerical modelling techniques.

Furthermore, many available CFD studies focus primarily on general combustion characteristics, fuel-air mixing, or pollutant formation rather than evaluating the specific effects of burner port geometry under standardised domestic cooking conditions. As a result, the relationship between burner port diameter, combustion behaviour, heat transfer mechanisms, and thermal efficiency remains insufficiently understood.

This gap emphasises the need for a detailed CFD-based investigation to quantify how variations in burner port diameter affect thermal efficiency in domestic biogas cookstoves. Such research would provide valuable design guidance for improving burner performance, reducing fuel consumption, and enhancing the overall effectiveness of biogas as a sustainable household cooking fuel.

METHODOLOGY

3.1 Research Design

A numerical CFD approach was adopted using ANSYS Fluent 16.0.

3.2 Geometry Development

The computational model consisted of:

- 25° burner sector;
- Cylindrical vessel wall;
- Burner cap;
- Combustion region;
- Surrounding air domain.

3.3 Mesh Generation

A structured tetrahedral mesh was generated using ANSYS DesignModeler.

Grid Independence

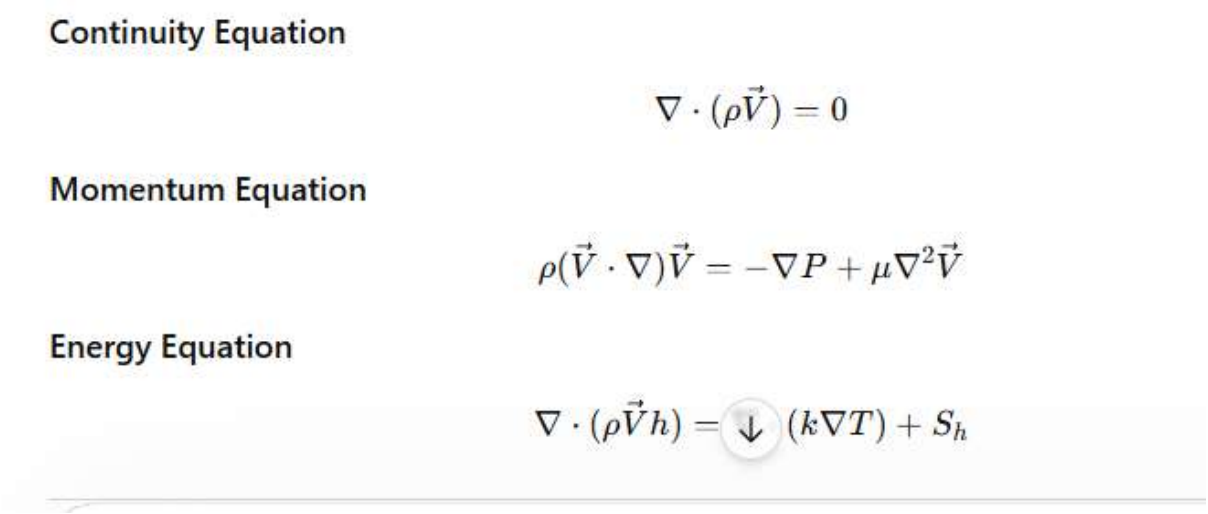
Three mesh densities were evaluated:

Mesh	**Elements**
Coarse	0.45 million
Medium	0.82 million
Fine	1.25 million

The medium mesh was selected.

3.4 Governing Equations

The simulation solved:



Continuity Equation

$$\nabla \cdot (\rho \vec{V}) = 0$$

Momentum Equation

$$\rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \mu \nabla^2 \vec{V}$$

Energy Equation

$$\nabla \cdot (\rho \vec{V} h) = (k\nabla T) + S_h$$

3.5 Turbulence Model

The standard k–ε turbulence model was employed because of its robustness in burner simulations.

3.6 Species Transport Model

Biogas combustion was modelled using a two-step global reaction mechanism.
Fuel composition:

Species	Fraction
CH_4	0.485
CO_2	0.515

3.7 Radiation Model

The Discrete Ordinates (DO) model was used to capture radiative heat transfer.

3.8 Boundary Conditions

Parameter	Value
Fuel flow rate	4 LPM
Injector diameter	2.5 mm
Vessel diameter	180 mm
Vessel height	100 mm
Loading height	25 mm
Wall temperature	300 K

3.9 Thermal Efficiency Calculation

Thermal efficiency was determined according to IS 8749:2002:

$$\eta = \frac{m_w c_p (T_f - T_i)}{m_f CV} \times 100$$

RESULTS AND DISCUSSION

4.1 Flame Temperature Distribution

The CFD results show peak temperatures close to the burner ports.
Maximum flame temperature:

$$T_{max} \approx 2400K$$

Hot gases move radially outward and upward due to buoyancy forces.

4.2 Influence of Burner Port Diameter

3.5 mm Port

- Stable flame
- Slightly lower heat release
- Reduced vessel temperature

4.0 mm Port

- Optimum flame structure
- Highest heat transfer
- Maximum efficiency

4.5 mm Port

- Similar behaviour to 4 mm
- Slightly lower performance

5.0 mm Port

- Lower jet velocity
- Reduced flame intensity
- Lower average vessel temperature

4.3 Vessel Bottom Temperature

A dual-peak temperature profile was observed.

Peak 1:

Direct flame impingement region.

Peak 2:

Radial distance of approximately 50–80 mm.

This confirms earlier observations regarding domestic gas burner heat transfer mechanisms.

4.4 Heat Transfer Characteristics

The majority of useful energy transfer occurred through:

1. Forced convection;
2. Radiation;
3. Flame impingement.

The 4 mm burner demonstrated the highest average heat flux.

4.5 Thermal Efficiency Analysis

Port Diameter (mm)	Efficiency (%)
3.5	60.11
4.0	61.64
4.5	61.02
5.0	58.87

The 4 mm configuration produced the best thermal performance.

4.6 DISCUSSION

Results agree with previous studies reporting superior performance for approximately 4 mm flame port diameters in biogas burners. Improved efficiency results from enhanced fuel-air mixing and optimal flame impingement on the cooking vessel.

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study numerically investigated the influence of burner port diameter on a domestic biogas cookstove burner.
Major findings include:

1. Maximum flame temperatures reached approximately 2400 K.
2. Burner port diameter influenced flame shape and heat transfer characteristics.
3. A dual-peak temperature distribution occurred on the vessel bottom.
4. The 4 mm burner port produced the highest thermal efficiency.

5. Burner port diameter has a moderate but significant effect on cookstove performance.

5.2 Contribution to Knowledge

The study provides CFD-based evidence that optimised burner port geometry can improve biogas cookstove efficiency without increasing fuel consumption.

5.3 Recommendations

1. Investigate burner port spacing effects.
2. Study flame stability under variable biogas compositions.
3. Conduct experimental validation of CFD predictions.
4. Evaluate emissions performance.
5. Develop multi-objective optimisation models incorporating efficiency and pollutant reduction.

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