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Research Paper

Comparative study on the combustion characteristics of an atmospheric induction stove in the plateau and plain regions of China

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HIGHLIGHTS

- Comparative combustion experiments are conducted in the plain and plateau regions.
- Combustion characteristics were measured for an atmospheric induction burner.
- Heat load reduces with altitude increasing.
- High altitude contributes to enhance thermal efficiency.
- CO and NO_x emission trend differently, CO rises but NO_x descends.

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ABSTRACT

Heat input, thermal efficiency, and emissions behaviour are the key performance characteristics of domestic gas appliances, which considerably depend on altitude. Because of the low atmospheric pressure and oxygen contents on the Tibetan Plateau, atmospheric induction stoves designed for plain areas tend to exhibit poor combustion performances when operated on a plateau, where poor energy utilization and indoor-air pollution are specific issues. In this study, a comparative study was conducted in a plateau and plain region of China to investigate the influence of altitude on a natural gas stove's combustion characteristics. The experimental results indicated that: (1) enhancing the gas supply pressure can eliminate the effect of altitude on the heat input; (2) there is a larger heat loss and higher thermal efficiency during incomplete combustion in Lhasa; and (3) oxygen-lacking conditions promote the formation of carbon monoxide and the lower flame temperatures reduce the emission of nitrogen oxides.

1. Introduction

The natural gas industry has been developing in China for more than 30 years and has become an important market. It is a statistical fact that China's energy consumption growth rate dropped from 7.0% to 4.7% in 2013 and thus is well below its ten-year trend [8.6% p.a.] [1]. To achieve the target energy savings and emission reductions, many efforts were made to increase the share of natural gas in the energy structure of China (currently 5.1%).

For many years, limited economic opportunities and the prices of fossil fuels led to dung cake being widely used for cooking and heating in Tibet. The wide-spread combustion of dung resulted in severe indoor air pollution [2]. Some combustion products of dung are harmful to human health and others have climate impacts [3–5]. As the first liquefied natural gas (LNG) fuelling station was put into operation [6], natural gas began to play an important role as an energy source in Lhasa, Tibet and was widely used in many combustion process, such as in public and commercial transportation applications and in domestic appliances [5].

Since the appearance of the Bunsen flame, a number of researchers have contributed to the optimization and improvement of the combustion process and applied it to the production of instruments and appliances employing a Bunsen flame. One of the main objectives for designers of domestic cooking stoves is to obtain higher efficiencies and lower pollutant emissions. In recent years, a number of studies on the thermal efficiencies and emissions of domestic gas-fired burners have been carried out [7–15]. Improvements in efficiency are important, such that even a slight improvement could lead to a significant overall impact on the economy of fuel usage. Hence, it is essential to raise thermal performance and reduce indoor-air pollution [15]. Researchers have

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Nomenclature

α	excess air factor, dimensionless
u	mass injecting ratio, dimensionless
s	relative density of gas, dimensionless
F	dimensionless area, dimensionless
K_1	energy loss coefficient of burner caput, dimensionless
F_1	burner parameters, dimensionless
$q_{V,c}$	converted gas flow, m^3/h
$q_{V,f}$	gas volume flow, m^3/h
t_g	gas temperature, °C
P_g	absolute pressure of dry gas, kPa
P_a	atmospheric temperature, kPa
P_m	gas relative static pressure in wet gas meter, kPa
S	saturated water vapour partial pressure at t_g, kPa
Φ_f	actual heat input, kW
Q_1	gas low heating value in standard conditions, MJ/m^3
η	measured thermal efficiency, %
M	mass of heated water, kg
C	specific heat of water, C = 4.19 kJ/(kg °C)
t_1	initial water temperature, °C
t_2	final water temperature, °C
V	gas consumption volume, m^3
$\varphi(CO)$	CO concentrations in dry flue gas under $\alpha = 1$, %
$\varphi(CO)_f$	actual CO concentrations in dry flue gas, %
$\varphi(CO_2)_c$	theoretical CO_2 concentrations in dry flue gas, %
$\varphi(CO_2)_f$	actual CO_2 concentration in dry flue gas, %
$\varphi(CO_2)_{f,a}$	actual CO_2 concentration in dry indoor air, %
$\varphi(NO_x)$	NO concentration in dry flue gas under $\alpha = 1$, %
$\varphi(NO_x)_f$	actual NO concentration in dry flue gas, %
$\varphi(NO_x)_{f,a}$	actual NO concentration in indoor air, %
$\varphi(O_2)_f$	actual O_2 concentration in dry flue gas, %
P_f	oven former relative pressure, Pa

put forward many improvements [10,12,16,17] to optimize combustion behaviour.

However, the environment on the Tibetan Plateau is entirely different from the conditions of previous research studies and may deteriorate combustion. Especially for those cooking applications designed for a plain area, operation at high altitudes can cause the following problems: decrease in heat input, incomplete combustion, emissions of carbon monoxide, and so on.

Law [18] noted that the laminar flame velocity is a property of fuel choice and therefore depends on the chemical composition of the fuel mixture, the temperature and the pressure. Amell et al. [19] investigated the laminar burning velocity of syngas mixtures at an altitude of 2130 m above sea level (m.a.s.l) (0.776 atm) and 21 m.a.s.l (0.994 atm) to evaluate the dependence of the laminar burning velocity on the pressure, flame temperature and relative humidity. The results indicated that at an equivalence ratio of 1.1, the laminar burning velocity at lower pressure increased by almost 23% with respect to the sea level condition. Hugo [20] carried out experiments in real sub-atmospheric conditions at three different altitudes, 500, 1550, and 2300 m.a.s.l. The results noted that the laminar burning velocity at sub-atmospheric pressures considerably depends on the equivalence ratio. Wieser et al. [21] conducted a series of comparative experiments at different altitudes (ranging from 400 m to 3000 m). It is observed that with the increase in altitude, the burning rate reduced because of the decrease in the atmosphere pressure.

Hu et al. [22] presented an experimental series of *n*-heptane pool fires at high altitudes. The study revealed that as the altitude increased, the burning rate, radiation heat flux and average flame axis temperature decreased. Amell [23] performed tests in Colombia at 40, 550, 1220, 2040 and 2550 m.a.s.l to determine the behaviour of the blue cone in a premixed flame. This study found that the height of the blue cone increased by 1.49 ± 0.12 mm for each 304 m rise in altitude. Iral and Amell [24] conducted a performance study of an induced air porous radiant burner using natural gas at an altitude of 1550 m.a.s.l to evaluate the characteristics of the burner's operation, such as the thermal efficiency and concentrations of CO and NO_x emitted into the atmosphere. The results indicated that it is not possible to achieve complete combustion in this burner due to a deficiency of primary air and lack of adequate and effective diffusion of secondary air.

Additionally, both American and European national standards institutes suggest choosing a nominal pressure related to the destination country and adjusting the heat inputs on the consumer-side [25,26].

Although several studies have investigated the influences of altitude on combustion, less work has been performed on the combustion characteristics and flue gas performance, especially under the sub-atmospheric and low-oxygen conditions found on the Tibetan Plateau. The primary objective of this study is to analyse the behaviour of an atmospheric induction stove in Lhasa. Furthermore, comparative experiments in plateau and plain regions of China were carried out to evaluate the individual and combined influences resulting from the Tibetan Plateau environment to help cope with the combustion-related issues.

2. Experiments and methodology

The combustion experiments were conducted in two places, a plateau (represented by Lhasa, at the latitude of 29°39′N and longitude of 91°18′E with an altitude of 3658 m.a.s.l) and a plain region (represented by Chongqing, at the latitude of 29°34′N and longitude of 106°27′E with an altitude of 400 m.a.s.l). The current gas source of Lhasa is LNG transported by tank cars from Golmud, Qinghai Province, and Chongqing receives piped natural gas (PNG). The temperament characteristics of the LNG provided to Lhasa are basically equivalent to the PNG found in Chongqing, which we confirmed using a theoretical calculation, shown in Table 1, so the differences between the LNG and PNG were considered to be negligible.

2.1. Experimental setup

The domestic gas burner used in this study is a so-called double ring burner, which is one of the most popular burners found on the

Table 1
The properties of Chongqing PNG, Lhasa LNG and 12T reference gas [27].

Fuel properties	PNG	LNG	12T gas
Hydrogen (vol.%)	0	0	0
Nitrogen (vol.%)	0	0.1500	0
Oxygen (vol.%)	0.7110	0.0190	0
Carbon monoxide (vol.%)	0	0	0
Carbon dioxide (vol.%)	0	0.047	0
Methane (vol.%)	97.0190	99.7000	100
Ethane (vol.%)	0.0220	0.0720	0
Propane (vol.%)	0.8260	0.0100	0
C4 (vol.%)	0.1970	0.0025	0
C5 (vol.%)	0.1840	0.0064	0
Gross calorific value (MJ/m^3)	40.0800	39.7800	39.8420
Net calorific value (MJ/m^3)	36.1500	35.7600	35.9020
Relative density	0.5600	0.5560	0.5550
Theoretical air quantity (Nm^3/Nm^3)	9.5370	9.5120	9.5240