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# Investigation of the transmitted noise of a combustor exit nozzle caused by burned hydrogen-hydrocarbon gases

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ABSTRACT

Transmitted noise is a major problem in industrial and aero-engine gas turbines. One of a noise generating part in the preceding systems is exit nozzle which can play as encouraging or discouraging sound waves. The generated noise may arise from an incident acoustic wave or entropy wave. In this paper, the effect of heat transfer and inlet Mach number of the exit nozzle as well as replacing the traditional hydrocarbon fuels with hydrogen and composite of hydrogen-hydrocarbon on noise generation is studied. Further, the influence of the hydrodynamic decaying mechanisms in a nozzle on the noise generated by entropy waves is investigated. It is found that hydrogen can reduce transmitted noise in a subcritical nozzle with an acoustic incident wave or in a supercritical nozzle with an incident entropic wave.


## Introduction

Moving toward the usage of alternative fuels due to hydrocarbon sources leakage, hydrogen has been interested in previous years. Although hydrogen has been an efficient fuel in on-ground industries such as power plants, this has been as a working fuel in aero-engine gas turbines from about half century later. Hydrogen is currently used in propulsion of many subsonic and supersonic flight engines [1]. One of the most important benefits of hydrogen fuel is related to the environmental pollution. Hydrogen burned gases are wholly free from carbon monoxide (CO), carbon dioxide ($CO_2$), sulphur oxides ($SO_x$), unburnt hydrocarbons (UHC), and smoke. The only released emissions, however, are water and nitrogen oxides ($NO_x$) which fall in a low level compared to the traditional fuels [2].

A major problem in combustion system, regardless the fuel used, is noise generation in the combustor exit nozzle against acoustic or entropic excitation wave [3]. Entropy waves are essentially density inhomogeneities that are produced by the unsteady combustion processes [4]. Entropy noises can be produced by accelerating or decelerating entropy waves in the flow [5]. They can be, for example, by passing entropy waves through a nozzle or guide vanes in the first stage of a gas turbine. The transmitted noises produce harsh environmental pollution, while, the reflection noises impact on stability of the combustion which may lead to serious operational

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problems and hardware damage [3]. Hence, during the last 30 years, many researches have been conducted to reveal the role of entropy and acoustic waves in the noise emission and combustion instability.

One of the first attempt to find the transmitted and reflected noise from a nozzle is belonged to Marble and Candel [6]. They found the analytical expressions for the noise produced by entropic or acoustic wave passing through a convergent-divergent nozzle. They applied the compact nozzle and Eulerian flow assumption. Their results have been a useful tool to calculate the transmitted and reflected noise up to now. Cumpsty and Marble [7] studied the noise generation in a gas turbine stage. They found that the noise was fully depended on the pressure gradient through the stage. Further, Cumpsty [8] compared the noise caused from acoustic, entropic and vorticity waves in a flow with heat release and concluded that the entropy noise was dominant. One the most solid experiments on the transmitted noise, especially entropy one, of a nozzle is the series work of Bake et al. [9,10]. They presented that the entropy noise was strongly Mach number dependent, especially at the low values.

In reality, all exit nozzles include heat transfer and hydrodynamic effects. Hydrodynamic mechanisms, such as vorticity generation and breakdown as well as interaction between flow and boundaries, can decay the entropy wave strength and thus, they can reduce the noise generation [11,12]. Transfer of heat can also modify acoustic and entropic waves. Further, it can affect the velocity field in compressible flows and therefore leaves an indirect influence on the acoustic waves [13,14]. It follows that these should be, therefore, involved in a realistic model of noise generation in nozzles. The problems of heat transfer in ducts have received some attentions in the literature [13–15]; in particular, Karimi et al. [13,14] demonstrated the significant effect of mean temperature gradient upon the reflection and transmission of acoustic and entropic waves. They studied various sound sources such as, steady and unsteady heat communications.

As stated above, the influence of heat transfer on noise generation is currently obvious [13,14] and accordingly, this should be considered in transmitted noise calculation. Further, in spite of many studies stated some of them above, one of the important keynotes partly missed in the literature is decay of the entropy waves and its relative effects on the noise generation. This can be due to whether cooling heat transfer or hydrodynamic mechanisms. Additionally, although some attentions have been devoted on the effect of fuel type in combustion instability [16–18] and combustion noise [19], no work has been focused on the transmitted noise rising from a burned gases of a traditional or novel composite fuel in an exit combustor nozzle; as the whole above studies applied hot air as the working fluid. These conditions, however, are really found in an exit nozzle of a combustor in industrial or aero-engine gas turbines. Thus, it follows that detection of a non-adiabatic nozzle response to entropy and acoustic waves, in the existence of hydrodynamic decaying mechanisms when an economical and clear fuel (hydrogen, for instance) is used, is central to predict the amplitude of the transmitted noises as this is seeking in the current work.

## Governing equations of motion

Before starting this section, the following assumptions should be noted.

(a) The heat sink is only radiative due to low residence time of the hot gases,
(b) cooling doesn't change the critical statues of the nozzle,
(c) there is no shock wave in the divergent part of the supercritical nozzle,
(d) there is no any friction losses,
(e) unsteady heat transfer will be negligible,
(f) the working fluid is an ideal gas with Newtonian, inviscid, non-heat-conducting characteristics. This is a mixture of the burned gases of hydrogen and hydrogen-hydrocarbon (means steam, carbon dioxide and nitrogen),
(g) the nozzle is assumed to be compact. This means the nozzle length is too small compared to the entropy and acoustic wave length.

The one-dimensional conservation equations of mass, momentum and energy are [13].

$$\frac{1}{\rho}\left(\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial x}\right)+\frac{\partial u}{\partial x}=0, \quad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+\frac{1}{\rho}\frac{\partial p}{\partial x}=0, \quad (2)$$

$$\frac{Ds}{DT}=\frac{q}{\rho T}. \quad (3)$$

In the above equations, p, ρ,u, s and t are respectively the static pressure (Pa), fluid density (kg/m$^3$), velocity (m/s), entropy (kJ/kgK) and time (s). Further, T is the fluid absolute temperature and q is the heat addition or loss per unit volume.

Flow variables are then substituted by the summation of the steady and perturbation parts such that $g=\overline{g}+g'$ in which g is a flow property. The following analysis will be on the basis of linear method. The linear methods have received many attentions due to its validity to predict combustion instabilities in a wide range when they combined in low order models [3]. The linear analysis has its comparable benefits, such as simplicity and accuracy in many engineering cases. Ignoring the second order terms results in the linearized form of mass, momentum and energy equations of (1)–(3). These are

$$\left(\frac{\partial}{\partial t}+\overline{u}\frac{\partial}{\partial x}\right)\frac{\rho'}{\overline{\rho}}+\overline{u}\frac{\partial}{\partial x}\left(\frac{\acute{u}}{\overline{u}}\right)=0, \quad (4)$$

$$\frac{\partial}{\partial t}\left(\frac{\acute{u}}{\overline{u}}\right)+\overline{u}\frac{\partial}{\partial x}\left(\frac{\acute{u}}{\overline{u}}\right)+\frac{\rho'}{\overline{\rho}}\frac{\partial \overline{u}}{\partial x}+2\overline{\rho}\overline{u}\frac{\acute{u}}{\overline{u}}\frac{\partial \overline{u}}{\partial x}+\overline{p}\frac{\partial}{\partial x}\left(\frac{p'}{\overline{p}}\right)+\frac{p'}{\overline{p}}\frac{\partial p'}{\partial \overline{p}}=0, \quad (5)$$

$$\frac{Ds'}{Dt}=\frac{\overline{q}R}{\overline{p}}\left(\frac{q'}{\overline{q}}-\frac{u'}{\overline{u}}-\frac{p'}{\overline{p}}\right). \quad (6)$$

It, further, follows from the first law of thermodynamics that