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論文題目	Numerical Investigation of Combustion Noise of Turbulent Flames （数値解析による乱流火炎の燃焼騒音に関する研究）		

（論文内容の要旨）

In this thesis, the combustion noise generated by an open turbulent spray flame is predicted and its characteristics are investigated using different numerical strategies, namely DNS (Direct Numerical Simulation) and hybrid DNS/CAA (Computational Aero-Acoustics) approach, in addition to investigations of combustion noise of turbulent non-premixed flames. This thesis consists of 5 chapters.

In Chapter 1, the background and motivation for this study along with the outline of the thesis are described.

Chapter 2 describes the DNS of combustion noise from open turbulent non-premixed hydrogen flames. DNS is used to analyze the direct combustion noise generated by two open turbulent non-premixed hydrogen jet flames, having the same nitrogen-diluted hydrogen fuel composition (H_2/N_2 : 50/50 volume %), and with different Reynolds numbers of *Re* = 6200 (Case H5) and *Re* = 10000 (Case H3). A one-step global reaction model is used for describing hydrogen combustion reaction. The DNS results of flow-field statistical quantities are validated against experimental data for both hydrogen flames. Comparison of the computed sound intensity level spectra with experimental data for the flame in Case H3 also shows favorable agreement. Combustion noise generated by both the turbulent non-premixed flames is broadband in nature. Analysis of the spectral content of noise generated by both flames reveals strong influence of the monopole-type combustion noise sources on the sound pressure field, while the influence of the quadrupole-type turbulence noise sources is found to be negligible. Next, the mechanism influencing combustion noise generation due to variation in Reynolds number of the two non-premixed flames is investigated. Higher turbulent velocity fluctuations are observed in the flame with higher *Re* (Case H3) compared to the flame with lower *Re* (Case H5), which causes greater fluctuations of heat release rate for the flame in Case H3. Consequently, the combustion noise sources arising from the heat release rate fluctuations are stronger for the flame in Case H3 compared to those in Case H5. Hence, the combustion noise generated by the flame with higher *Re* (Case H3) is found to be louder than that of the flame with lower *Re* (Case H5).

Chapter 3 describes the characteristics of combustion generated noise of an open turbulent spray flame. The combustion noise generated by an open turbulent spray flame with ethanol as fuel (Case EtF3, *Re* = 19700) is investigated by means of DNS, employing an Eulerian-Lagrangian framework with two-way coupling. A two-step global reaction model is used to account for combustion chemistry. The DNS predictions for flow-field statistical quantities show an overall good agreement with experimental data. The turbulent spray flame exhibits combustion noise characteristics similar to those of turbulent non-premixed flames in general. Namely, the broadband spectra of direct combustion noise, and noise directivity characteristics that show similar spectral shapes and nearly same sound pressure levels at the low-frequencies for various emission angles to the flame axis, suggesting the dominance of distributed monopole combustion noise sources. For the high-frequency noise emissions on the other hand, reduction of sound pressure levels with increasing distance from the nozzle exit (corresponding to decreasing emission angle to the flame axis) is observed. The reason for the weak directivity of the high-frequency noise emissions is attributed to refraction effects arising from temperature-dependent gradients in the sound speed within the flame, which is confirmed from the DNS results for stream-wise variations of frequency-filtered OASPL (Overall Sound Pressure Level), along with evidence from previous experimental and numerical studies on turbulent non-premixed flames in general.

Chapter 4 describes the application of a hybrid CFD/CAA approach to an open turbulent spray flame and an open turbulent non-premixed flame. The relatively new numerical framework of the hybrid CFD/CAA approach is applied to the turbulent spray flame (Case EtF3, *Re* = 19700) in Chapter 3, and the turbulent non-premixed flame (Case H3, *Re* = 10000) in Chapter 2, to predict and analyze the radiation of combustion generated noise in the far-field. In this two-step framework, the first step involves a DNS of the reacting flow-field of the turbulent flame (within which the sources exciting acoustic waves are present), while the second step involves a CAA simulation that is performed by solving the Acoustic Perturbation Equations extended for Reacting Flows (APE-RF), to capture the acoustic wave propagation all the way into the far-field. This numerical approach, termed as the hybrid DNS/APE-RF approach in this study, is a computationally efficient and cheaper alternative to performing a compressible DNS simulation of a turbulent flame, on a large computational domain that extends up to the acoustic far-field. In order to incorporate the additional effect of density variations caused by fuel droplet evaporation, the source term dominating the excitation of acoustic waves in combustion noise is newly derived for the spray flame (Case EtF3). The results obtained from the hybrid DNS/APE-RF approach for combustion noise spectra of the spray flame (Case EtF3) in the far-field, reveal the characteristics similar to those of turbulent non-premixed flames in general. Such as, broadband shape of the spectra, nearly constant sound pressure levels in the low- and mid-frequencies for various radiation angles to the flame axis, and the attenuation of high-frequency noise radiated to the far downstream locations from nozzle exit, which is caused by acoustic refraction effects arising from sound speed gradients within the flame. This means that the hybrid DNS/APE-RF approach developed in this study is capable of accurately capturing the characteristic of radiation of combustion generated noise even in the far-field.

Chapter 5 summarizes all the investigations carried out in this study and recommendations for possible future extensions of the present research are provided.

（続紙 ２ ）

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（論文審査の結果の要旨）

本論文は，乱流火炎の燃焼騒音に関する研究の結果をまとめたものであり，得られた主な成果は以下の通りである．

1. 水素・空気乱流拡散噴流火炎の直接数値シミュレーション (Direct Numerical Simulation, DNS) により，拡散火炎から発生する音波は幅広い周波数帯域に分布すること，また，四極子の乱流騒音源よりも単極子の燃焼騒音源の影響をより強く受けることを明らかにした．さらに，レイノルズ数の増大に伴い，乱流変動の増加が発熱率変動を増加させることにより，燃焼騒音は増大することを明らかにした．
2. 液体燃料としてエタノールを用いた乱流噴霧噴流火炎の DNS により，噴霧火炎から発生する音波は拡散火炎から発生する音波と同様に幅広い周波数帯域に分布し，その音圧レベルは火炎の下流位置によらず低周波数帯域ではほぼ不変であるが，高周波数帯域では下流に行くにつれて低下することを明らかにした．また，この高周波数帯域における音圧レベルの低下が，火炎内の温度分布による音速の変化を原因とする音波の屈折効果に起因することを明らかにした．
3. 燃料液滴の蒸発が燃焼騒音源に及ぼす影響を解明し，その影響を反応流に適用可能な音響摂動方程式 (Acoustic Perturbation Equations extended for Reacting Flows, APE-RF)中の生成項として厳密にモデル化した．また，この APE-RF と DNS を組み合わせた数値解析手法（DNS/APE-RF）が乱流噴霧火炎の遠方領域における燃焼騒音の予測に有効であることを明らかにした．

以上，本論文は，気体および液体の燃料を用いる乱流火炎を対象に，音波の発生・伝播を高精度に予測可能な数値シミュレーション手法を確立するとともに，その燃焼騒音特性を明らかにしたものであり，学術上，実際上寄与するところが少なくない．よって，本論文は博士（工学）の学位論文として価値あるものと認める．また，平成３０年２月２０日，論文内容とそれに関連した事項について試問を行って，申請者が博士後期課程学位取得基準を満たしていることを確認し，合格と認めた．