Unsteady Behavior Droplet Combustion in Forced Convection(強制対流場における液滴燃焼の非定常挙動に関する研究)

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論文内容要旨

The objectives of the present study were to explore the fundamental mechanisms of the combustion of a fuel droplet in unsteady oscillatory flow, especially at elevated pressure. The present study is of importance because of our very limited knowledge of the phenomena during combustion/evaporation of a fuel droplet in the presence of airstream fluctuations. The knowledge obtained by this study gives us new insights into the effects of turbulence on the evaporation and combustion of fuel sprays, which is essential for improving the performance of practical spray combustors.

The present Ph.D. project consisted of two parts. In the first part, an extensive experimental study was performed to observe the behaviors of a single suspended burning droplet under microgravity conditions. The drop-shaft facility at MGLab located in Toki City, Japan was used to conduct the experiments. In the second part, an original computational code was developed for reproducing and simulating experimental data on vaporization and combustion under microgravity conditions in order to investigate the involved mechanisms. The code is based on the finite volume method using SIMPLE algorithm for solving the flow field. The viscous effects, unsteady effects and all the transient processes in both liquid and gas phases, as well as the chemical reaction in the gas phase were included. The experimental and numerical results of the present study clearly show the inability of current classical quasi-steady model, which is widely used in contemporary spray modeling for predicting the vaporization/combustion of fuel droplets in the presence of flow fluctuation.

After the first chapter, in which the background of this study is presented, in the second chapter, interesting new findings of the experimental studies are presented, namely, the domination of the droplet lifetime by maximum value of the upstream velocity, which means a significant enhancement of the burning rate in the presence of flow oscillation and hysteresis behavior in burning rate in oscillatory flow. None of these phenomena can be described by quasi-steady models.

In the third chapter, based on precise experimental observations and by utilizing dimensional analysis of the energy conservation equation, a new criterion is proposed for the condition in which the quasi-steady assumption is valid and for that

in which it is not. The dimensional analysis led to formulations of a new time scale. Based on this time scale, which we call the response-timescale, a new Damköhler number, termed the response-Damköhler-number was formulated. Using the definition of the new time scale and that of the Damköhler number, unsteady behaviors of droplet combustion under conditions of various pressures and varying force convection were examined. Using the response-Damköhler-number and the deviation factor between the actual instantaneous burning rate and the burning rate predicted by the quasi-steady theory, droplet combustion is categorized into four specific regimes.

Another part of this project was the development of an original numerical code to investigate the phenomena observed in the microgravity experiments. The fourth chapter details development of this for simulating an evaporating fuel droplet without combustion in unsteady forced convection to understand the behavior of vaporizing boundary layer around droplet in a hot oscillatory convective airstream as a first numerical approach. The validity of the code was examined by comparison between present numerical results and the existing numerical simulations, as well as with reference to experimental data on the flow over a sphere and evaporation of a suspended droplet in microgravity. Excellent agreement between our results and those reported in the literature for the flow over a sphere was confirmed. The value of the Nusselt and Sherwood numbers, the reattachment length in the wake region and the separation angle were the parameters used for comparisons. The time history of the square of the droplet diameter calculated in this study was compared with numerical results of other researchers and experimental data reported in the open literature for an n-heptane fuel droplet in a hot quiescent atmosphere. In the case of a fuel droplet in a hot airstream, a vaporizing n-decane fuel droplet was simulated and the results were compared with the experimental and numerical data available in the literature. There was good agreement between the two.

After examination of the validity of the code, an evaporating droplet in oscillatory flow was numerically investigated. Since these calculations were conducted to explore the features of the flow pattern in low frequency upstream oscillatory velocity consistent with the conditions of the microgravity experiments, the examined frequencies were chosen from 1 Hz to 75 Hz with an oscillation Reynolds number Re_a from 2.5 to 80. The response of evaporation to the variation of the oscillation frequency and amplitude were investigated separately.

The numerical results showed that with increasing amplitude of oscillation, the evaporation rate increased. As for the response of the evaporation to the frequency of oscillation, it was found that the response occurred in different modes depending on the frequency and amplitude of the oscillation. One mode of the response is synchronous with the main flow oscillation and is not sensitive to the changing of the oscillation frequency. The quasi-steady condition was attained, contrary to what occurred in the other mode where the response was asynchronous with the main flow oscillation and was unsteady. However, the evaporation rate in all conditions was shown to be enhanced in oscillatory flow compared with that in quiescent air.

To quantify the conditions of the transition from the quasi-steady to the unsteady response, use of the oscillation Strouhal number S_{osc} was proposed in this study. This number shows whether the time scale of the oscillation compared with the flow time scale is sufficiently long to let the boundary layer around the droplet reach the quasi-steady condition or not. The numerical results showed that at a low S_{osc}, a quasi-steady boundary layer was formed, whereas by increasing the S_{osc}, the quasi-steady condition could not be attained.

The fifth chapter details numerical analysis of droplet combustion in oscillatory convective flow at elevated pressure performed including the chemical reaction in the code. The validity of the numerical results was examined by comparison with the experimental data obtained from microgravity experiments for combustion of a single suspended 1-butanol droplet performed in the present study. The time history of the normalized square of droplet diameter and the position of the bow point in Schlieren images were the parameters used for comparisons.

In excellent agreement with the experiments, the numerical results showed that oscillation of flow significantly enhanced the burning rate compared with that of the burning rate in a constant flow. Numerical results confirmed that the lifetime of a single suspended droplet is dominated by the maximum value of the velocity, this finding being absolutely consistent with microgravity experiments. Since the experimental wave forms of the upstream velocity oscillation used in microgavity experiments were complicated, it was first required to show that the pattern of oscillation does not change the outline of the overall vaporization processes. Therefore, several cases of the oscillation wave form were examined in order to clarify the identical characteristics of droplet behaviors in oscillatory flow.

After the clarification of the effects of the specific oscillation wave forms on the overall processes, local responses of the boundary layer to the flow oscillation were investigated to explore the phenomena that are responsible for the enhancement. Results showed that depending on the oscillation Reynolds number, there are three mechanisms that result in the enhancement. At a low oscillation Reynolds number, $Re_{osc} = 30$, the first mechanism of the enhancement, herein termed diffusion-time-delay is dominate. In this condition it was shown that the flame in the forefront of a droplet during the deceleration period does not return to its position in a constant flow with equivalent velocity. This is due to a diffusion-time-delay that is required for the flame to adapt to the upstream variation.

At a large oscillation Reynolds number, e.g., $Re_{osc} = 100$, the second mechanism, i.e., vortex-flow motion, is dominate. This vortex motion was generated outside of the droplet flame and subjected to the positive pressure gradient behind of the droplet, which led to the movement of the flame to the droplet surface in the wake region. These effects are significant at high pressure because of the decreasing of the vortex dissipation rate, which is a consequence of decreasing kinematic viscosity at elevated pressure. The movement of the flame results in a decrease of the average distance between the flame and the droplet surface in the wake region compared with that at constant flow with an equivalent velocity, thus the local evaporation rate is significantly enhanced there.

Different from the first mechanism (diffusion-time-delay) and second mechanism (vortex-flow motion) of the burning rate enhancement, which are influential in the deceleration period, the third mechanism, that is overshooting, affects the phenomena during the acceleration period. Overshooting of *K* during the flow acceleration compared with that in an equivalent constant flow velocity is a consequence of the increase in the forefront of translative flow momentum. When the flow with high inertia approaches the droplet, flame moves closer to the droplet before its momentum balances with the Stefan-flow generated by vaporized fuel. This results in an increase in the gradient of temperature at the flame in oscillatory flow compared with that in the case of constant flow. This increase of the temperature gradient causes an increase of the heat conducted from the reaction zone to the droplet, i.e., enhancement of the burning rate and overshooting of *K*.

The contribution of the enhancement of burning rate in the low velocity interval is much larger than that for the high velocity interval in all conditions with a wide range of Reynolds numbers. However, at a large oscillation Reynolds number, the phenomena are highly convective controlled. The strong convection in these conditions is provided by the vortex-flow-motion, which is mainly generated and affects the wake region of the droplet. Therefore, in this condition, enhancement of the evaporation rate in the wake region of the droplet is the main factor which contributes to the total enhancement of burning rate.

Contrarily, at a low oscillation Reynolds number, although the interval of the low velocity contributes to the enhancement of the burning rate, since the generated vortex-flow-motion is weak, the phenomena at low velocity are highly diffusion controlled. In this order, the enhancement of the burning rate in the forefront of the droplet caused by the diffusion-time-delay mechanism, the first mechanism of the enhancement, to the total enhancement of burning rate.

The overshooting effect is amplified at elevated pressure and high frequency. Since the density of gas at high pressure is large, acceleration of the flow results in a greater increase in flow inertia, hence a larger overshooting of *K*. Oscillation of the flow with higher frequency also increases the flow acceleration, which means a larger increase in flow inertia, and leads to larger overshooting of *K*.

Finally, after the investigation of the hysteresis behavior of burning rates in various oscillation patterns, the mechanism of the hysteresis was examined. To this end, numerical results for a burning droplet at oscillatory flow in which the upstream velocity oscillates with a step pattern was used. It was clarified that the hysteresis behavior is a consequence of the difference in the response of the flame to deceleration compared with that to the acceleration of upstream velocity during its oscillation.

The sixth chapter provides a summary and conclusions of the previous chapters.

論文審査結果の要旨

高圧環境下の乱流噴霧燃焼はガスタービン燃焼器など実用高負荷燃焼器の基本燃焼形態であり，その高度な制御と数値予測には素過程である液滴燃焼現象の解明が不可欠である。乱流中の液滴燃焼は乱れによる酸化剤の相対速度変動に特徴が見出されるが，従来の乱流噴霧燃焼解析は液滴燃焼に準定常仮定を用いており，その妥当性には疑問があった。本研究は，高圧環境下の乱流場における液滴燃焼特性を予測するため，特に液滴燃焼に対する対流速変動効果に注目し，周期的な流速変動が液滴火炎に及ぼす影響を微小重力実験と数値解析によって明らかにした。本論文は，これらの研究成果をまとめたものであり，全編6章からなる。

第1章は序論であり，本研究の背景，目的および構成を述べている。

第2章では，落下実験施設において直径約1 mm の 1-ブタノール単一液滴に対し 1.0 MPa までの高圧環境における微小重力燃焼実験を行い，高圧環境ではいずれの空気流速変動周波数においても燃焼速度定数が変動流速の最高流速に支配されること，瞬時燃焼速度定数の変化にヒステリシスが生じることを明らかにしている。これは変動流速場における液滴燃焼の非定常特性として注目すべき発見である。

第3章では，微小重力実験により見出された二つの非定常特性が従来の準定常仮定の限界を示しているとの観点から準定常理論を見直し，非定常エネルギー方程式の次元解析によって流速変動の特性時間と熱・物質拡散の特性時間の比から成る応答ダムケラ数を新たに提案し，応答ダムケラ数が減少すると準定常仮定が成立しなくなることを明らかにしている。これは燃焼学的に非常に重要な知見である。

第4章では，次章で行う化学反応を伴う数値解析に先立ち，正弦波形で往復変動する高温空気流中における液滴蒸発の数値解析コードを新たに開発し，n-ヘプタンに対して計算を行って雰囲気圧力 0.5 MPa における蒸発特性を調べている。その結果，変動振幅が増大すると常に蒸発速度定数が増大し液滴寿命が減少するが，変動周波数が増大すると流速変動に追従しなくなり液滴寿命も長くなることが示され，液滴後流に残留する渦の影響を受ける境界層形成の非定常性に起因する現象であることを明らかにしている。これは，乱流噴霧の蒸発特性を理解する上で重要な知見である。

第5章では，前章で開発した数値解析コードに化学反応項を加えて液滴着火から燃焼まで計算が可能な数値解析コードを完成させ，微小重力実験と同条件の数値解析を行い，実験結果を数値的に再現することに成功している。特に，燃焼速度定数が変動流速の最高流速に支配されるメカニズムとして，よどみ点近傍における火炎の移動に遅れを生じさせる応答ダムケラ数に対応する拡散時間遅れ効果，液滴火炎の斜め後方に形成される渦によって液滴後端近くの火炎が液滴に接近し蒸発を促進する効果，最大流速に達する際に空気流の慣性力によって火炎が液滴に接近し温度勾配が増大して加熱が促進される効果の三つの効果を明らかにしている。さらに，瞬時燃焼速度定数におけるヒステリシスについて，これら三つの効果が存在する場合に，空気流の加速および減速時では流速変動への応答性が異なることが原因であることを示している。これらは，変動速度場において液滴火炎の準定常仮定が適用できないメカニズムを明確にしたもので，液滴燃焼の現象解明のみならず，乱流噴霧燃焼のモデリングを高度化するために非常に重要な成果である。

第6章は結論である。

以上要するに本論文は，高圧環境下において流速が変動する強制対流場での液滴燃焼の非定常挙動と準定常仮定の限界，およびそのメカニズムを微小重力実験と数値解析によって明らかにしたもので，航空宇宙工学および燃焼工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。