令和5年度原子力規制庁委託成果報告書

東京電力福島第一原子力発電所事故時の水素爆発における可燃性有機ガスの影響に関する調査

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1. 事業名

令和5年度原子力施設等防災対策等委託費(東京電力福島第一原子力発電所事故時の水素 爆発における可燃性有機ガスの影響に関する調査)事業

2. 事業目的

東京電力福島第一原子力発電所(以下「1F」という。)事故等を踏まえた重大事故時の対策や 安全評価手法並びに安全対策の高度化に関連する技術的知見を取得する。本事業では、1F1 号機及び3号機の原子炉建屋において発生した爆発現象に関して、水素濃度等及び可燃性有機 ガスの影響を把握することを目的に、水素及び可燃性有機ガス濃度、初期ガス温度をパラメータ として、火炎色等確認試験(拡散燃焼試験)及び予混合燃焼試験を計画し実施する。

3. 事業内容

3.1 概要

本事業では、水素及び可燃性有機ガスの燃焼による水素燃焼時の挙動を把握するため、水素 及び可燃性有機ガスの濃度、初期ガス温度等をパラメータとして、下記に示す燃焼試験等を実施 する。

- (1)火炎色等確認試験(拡散燃焼試験)の計画及び実施
- (2)水素等燃焼試験(予混合燃焼試験)の計画及び実施
- (3)水素及び混合気体燃焼に関する最新知見の収集
- (4)報告書の作成

試験の条件設定に関しては、原子力規制庁が実施した令和4年度原子力施設等防災対策等 委託費(東京電力福島第一原子力発電所事故時の水素爆発における可燃性有機ガスの影響に 関する調査)事業の結果を参考とする。 3.2 実施内容

3.2.1 火炎色等確認試験(拡散燃焼)の計画及び実施

水素ガス及び可燃性有機ガスの火炎色等確認試験の計画及び試験を行う。燃焼試験では、水 素ガス及び可燃性有機ガス流量を調整し、拡散燃焼を一定時間維持する。なお、試験の計画及 び実施では、東京電力福島第一原子力発電所事故の調査・分析に係る中間取りまとめ[1,2]を参 考とする。

試験条件及び測定項目を以下に示す。

·試験条件

試験装置:ガス流量を調整し、拡散燃焼を一定時間維持

燃焼状態:拡散燃焼

水素濃度:0 vol% ~ 100 vol%

可燃性有機ガス(メタン)濃度:0 vol% ~ 100 vol%

不活性ガス(窒素)濃度:0 vol% ~ 50 vol%

·測定項目

水素ガス及び可燃性有機ガスの流量及び温度、記録用カメラによる燃焼 挙動(火炎色及び煙・煤等)、赤外線放射温度計等による火炎の温度分布

3.2.2 水素等燃焼試験(予混合燃焼)の計画及び実施

水素ガス、可燃性有機ガス及び空気の混合気体による燃焼試験の計画及び試験を行う。水素 等燃焼試験としては、次の2種類の燃焼試験(①水素燃焼試験、②混合気体(水素、可燃性有機 ガス及び空気)燃焼試験)とする。燃焼時の挙動を把握するため、口径 30cm 以上の観察窓を有 し、燃焼時の系内全体の挙動を観察・記録できる試験装置を用いて試験を行う。なお、試験の計 画及び実施では、東京電力福島第一原子力発電所事故の調査・分析に係る中間取りまとめ[1,2] を参考とする。

① 水素燃焼試験

デフラグレーション(deflagration、爆燃)を考慮した燃焼時の挙動を把握する試験を実施する。 試験パラメータは水素濃度及び初期温度とし、6 ケース実施する。ここでは、1 ケースあたり 3 回 の試験を行う。

試験条件及び測定項目を以下に示す。

・試験条件

試験装置:密閉型で、燃焼時圧力上昇に耐え、口径 30cm の観察窓を有する 燃焼状態:予混合燃焼 着火位置:中央部 水素濃度:10 vol%、15 vol%、20 vol% 初期温度:25 ℃、75 ℃ ·測定項目

水素ガスの濃度及び温度、燃焼時の系内の圧力変化、

高速度カメラによる燃焼挙動等

②混合気体(水素、可燃性有機ガス及び空気)燃焼試験

①の水素燃焼試験の結果を踏まえ、水素燃焼時の可燃性有機ガス(メタン)の影響を把握する ため、水素濃度、可燃性有機ガス濃度及び空気の混合気体による燃焼時の圧力変化並びに高 速度カメラによる燃焼挙動等を測定する。試験パラメータは、ガス濃度(水素及び可燃性有機ガス) 及び初期温度とし、12ケース実施する。ここで、混合気体の当量比は1以下とする。

試験条件及び測定項目を以下に示す。

・試験条件(試験装置、燃焼状態、着火位置は①と同様)

水素濃度:10 vol%、15 vol%、20 vol%

可燃性有機ガス(メタン)濃度:0 vol%、1 vol%、2 vol%

初期温度:25 ℃、75 ℃

·測定項目

水素ガス及び可燃性有機ガスの濃度及び温度、燃焼時の系内の圧力変化、 高速度カメラによる燃焼挙動等

3.2.3 水素及び混合気体燃焼に関する最新知見の収集

原子力発電所事故時の水素及び混合ガスの燃焼挙動に関する研究の最新動向を調査し、今後の事故分析に資するようにまとめる。調査範囲は文献及び海外研究機関の実験施設等とし、 必要に応じて海外研究者と意見交換を実施する。

3.2.4 報告書の作成

上記3.2.1~3について報告書にまとめる。報告書には、成果のみならず各試験における前 提条件及びプロセスも記載する。

4. 試験成果

- 4.1 火炎色等確認試験
- 4.1.1 試験装置

本試験では、水素/メタン混合気、水素/メタン/窒素混合気を取り扱い、内径 11 mmのブンゼン バーナーを用いて、拡散噴流火炎を形成させる。水素濃度、メタン濃度、窒素濃度、ガス総流量を 変化させて試験を実施し、燃焼挙動を観察すると共に火炎の温度分布等を測定する。

図1はブンゼンバーナーを示したものであり、管の内径は 11 mm、外径は 13 mm、長さは 97 mmである。



図1 ブンゼンバーナー



図2 燃焼試験システム

図2は燃焼試験システムを示したものである。火炎の画像は、デジタルカメラ(Nikon D5600)を 用いて、シャッター速度 1/15 s、F 値 7.1、ISO 感度 4000 及び有効画素数 2416 万画素で撮影し た。火炎の温度分布は、赤外線サーモグラフィカメラ(アビオニクス InfReC R300BP-OF)を用いて 測定した。このとき、放射率は R タイプ熱電対(線径 100 µm)による火炎温度から設定した。ガス が水素のみの場合は、微量(1-2%)のメタンを添加した。

4.1.2 試験条件とプロセス

ブンゼンバーナーに流入させる混合気は、初期温度 25℃(298 K)、初期圧力 1 気圧(101.3 kPa)、 所定の水素濃度(0~100 vol%)、所定のメタン濃度(0~100 vol%)、所定の窒素濃度(0~50 vol%) とした。ガス総流量は、1.0 L/min、2.0 L/min とした。このとき、平均流速は、それぞれ、0.18 m/s、 0.35 m/s である。ブンゼンバーナーに流入させる水素、メタン、窒素の流量は、デジタルマスフロ ーコントローラー(アズビル F4Q)で制御した。

ブンゼンバーナーに流入させる混合気における水素濃度、メタン濃度、窒素濃度は、表1の通り である。

表1 水素濃度、メタン濃度、窒素濃度

	100-0-0, 90-10-0, 70-30-0, 50-50-0,
H ₂ -CH ₄ -N ₂	30-70-0, 10-90-0, 0-100-0
	75-0-25, 67.5-7.5-25, 52.5-22.5-25, 37.5-37.5-25,
٢٥/٦	22.5-52.5-25, 7.5-67.5-25, 0-75-25
L70]	50-0-50, 45-5-50, 35-15-50, 25-25-50,
	15-35-50, 5-45-50, 0-50-50

4.1.3 試験結果と考察

水素/メタン混合気を取り扱い、ガス総流量が 1.0 L/min のときの拡散火炎の直接写真を示した のが図3である。水素濃度が高いときは、火炎を確認することが困難である。メタン濃度が高くな ると、薄オレンジ色の輝炎が観察される。これは遊離した炭素から発せられるものである。また、 バーナー出口近傍では、青色の炎が観察される。これは CH 発光によるものである[3]。

図4は、ガス総流量が 2.0 L/min のときの直接写真である。全体として、火炎は長くなる。水素 濃度が高いとき、薄い赤い炎が観察される。これは水蒸気の発光によるものである。なお、この薄 い赤い炎は、暗室における試験において確認されるものであり、屋外では水素火炎を目視で確認 することは困難である。

図5と図6は、ガス総流量が 1.0 L/min と 2.0 L/min のときの温度分布を示したものである。水素濃度が高いときの方が、温度は高くなる。また、ガス総流量が大きくなると、若干ではあるが温度は高くなる。

水素/メタン/窒素混合気を取り扱い、窒素濃度が25%、ガス総流量が1.0 L/minと2.0 L/minの ときの拡散火炎の直接写真を示したのが図7と図8である。混合気に窒素が加わる、つまり燃料 である水素とメタンの濃度が低下することにより、火炎は短くなり、火炎の色は薄くなる。図9と図 10は、ガス総流量が1.0 L/minと2.0 L/min のときの温度分布を示したものである。混合気に窒 素が加わることにより、温度は低下する。

窒素濃度をさらに高くし、50 % とする。図11と図12は、ガス総流量が 1.0 L/min と 2.0 L/min のときの直接写真を示したものであり、図13と図14は温度分布を示したものである。窒素濃度が さらに高くなると、火炎はさらに短くなり、火炎の色はさらに薄くなる。

火炎の最高温度を示したのが図15である。ガス総流量が大きくなると、最高温度は若干上昇 する。また、窒素濃度が高くなると、最高温度は低下する。これは、供給される燃料(水素とメタン) の量が少なくなるからである。さらに、水素濃度が高い方が、最高温度は高くなる。これは、水素 火炎温度の方がメタン火炎温度より高いからである。

拡散燃焼の試験では、全ての条件において、煙の発生は確認されなかった。一方、煤について は、メタンが燃料に含まれる場合、薄オレンジ色の輝炎が観察されていることから、その発生が確 認された。また、拡散火炎の上にスチール板を置いて試験を行い、その表面に煤が付着している ことを確認した。

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図3 火炎の直接写真 (ガス総流量 1.0 L/min、水素濃度 0~100 vol%、メタン濃度 0~100 vol%、窒素濃度 0 vol%)



図4 火炎の直接写真 (ガス総流量 2.0 L/min、水素濃度 0~100 vol%、メタン濃度 0~100 vol%、窒素濃度 0 vol%)



図5 火炎の温度分布 (ガス総流量 1.0 L/min、水素濃度 0~100 vol%、メタン濃度 0~100 vol%、窒素濃度 0 vol%)



図6 火炎の温度分布 (ガス総流量 2.0 L/min、水素濃度 0~100 vol%、メタン濃度 0~100 vol%、窒素濃度 0 vol%)



図7 火炎の直接写真 (ガス総流量 1.0 L/min、水素濃度 0~75 vol%、メタン濃度 0~75 vol%、窒素濃度 25 vol%)



図8 火炎の直接写真 (ガス総流量 2.0 L/min、水素濃度 0~75 vol%、メタン濃度 0~75 vol%、窒素濃度 25 vol%)



図9 火炎の温度分布

(ガス総流量 1.0 L/min、水素濃度 0~75 vol%、メタン濃度 0~75 vol%、窒素濃度 25 vol%)



図10 火炎の温度分布 (ガス総流量 2.0 L/min、水素濃度 0~75 vol%、メタン濃度 0~75 vol%、窒素濃度 25 vol%)



図11 火炎の直接写真

(ガス総流量 1.0 L/min、水素濃度 0~50 vol%、メタン濃度 0~50 vol%、窒素濃度 50 vol%)



図12 火炎の直接写真 (ガス総流量 2.0 L/min、水素濃度 0~50 vol%、メタン濃度 0~50 vol%、窒素濃度 50 vol%)



図13 火炎の温度分布

(ガス総流量 1.0 L/min、水素濃度 0~50 vol%、メタン濃度 0~50 vol%、窒素濃度 50 vol%)



図14 火炎の温度分布 (ガス総流量 2.0 L/min、水素濃度 0~50 vol%、メタン濃度 0~50 vol%、窒素濃度 50 vol%)





4.2.1 試験装置

本試験では、①水素/空気混合気(水素燃焼試験)、②水素/メタン/空気混合気(混合気体燃 焼試験)を取り扱い、水素濃度とメタン濃度を変化させて、口径 30 cm の観察窓を有する密閉型 容器内で燃焼試験を実施する。容器内に予混合気を充填し、中心点火することにより、球状のデ フラグレーション(deflagration、爆燃)を観察し、水素濃度による燃焼時の挙動及びメタン濃度によ る水素燃焼への影響を把握する。ここでは、シュリーレン法により、火炎伝播の様子や火炎面形 状を高速度撮影する。また、容器内の圧力変化を測定する。

図16は密閉型燃焼容器を示したものであり、表2はその基本仕様を示したものである。



図16 密閉型燃焼容器

表2 密閉型燃焼容器の基本仕様

容器	容積	73 L	
	材質	SUS	
	直径	300 mm	
観察窓	厚み	140 mm	
	数	4	



図17 燃焼試験システム

図17は燃焼試験システムを示したものである。燃焼容器には、ガス供給ライン、排気ライン、 真空引きラインを設け、ガス供給ラインと排気ラインのすべての弁は、遠隔から電気的に操作でき るように設定している。真空引きやガス供給時の容器内部圧力の測定用としてピエゾ抵抗センサ (Keller PAA-23Y)、容器内部の混合気温度の測定用にシース熱電対(T-type)を設置している。 燃焼時の容器内の急激な圧力変化を取得するため、圧電センサ(Kistler 6045A)を燃焼器上部に 設けたポートに直接取り付け、圧電センサ用チャージアンプ(Kistler 5918A)より出力された電圧を データロガー(キーエンス NR-600)によってサンプリング周波数 10 kHz で記録した。また、火炎 形状および動的な伝播挙動を広範囲に取得するため、直径 350 mm の凹面鏡を有するシュリー レン法測定装置(溝尻光学工業所 SL-350)により観察した。シュリーレン画像は、高速度ビデオ カメラ (Photron FASTCAM SA-X)を用いて、撮影速度 10000 fps、シャッター速度 20 µs、および 解像度 1024×1024 pixels で撮影した。

4.2.2 試験条件とプロセス

燃焼容器に充填する混合気は、初期温度 25℃(298 K)、75℃(348 K)、初期圧力 1 気圧(101.3 kPa)、所定の水素濃度(10 vol%、15 vol%、20 vol%)、所定のメタン濃度(0 vol%、1 vol%、2 vol%)とした。所定の水素濃度とメタン濃度になるように、分圧に関するドルトンの法則に基づいて気体を混合した。

燃焼試験では、容器内に①水素/空気混合気、②水素/メタン/空気混合気を充填した後、電極 により容器の中心で点火し、高速度ビデオカメラによるシュリーレン撮影、及び圧電センサによる 圧力測定を行った。燃焼試験は、①で6ケース、②で12ケース、全体で18ケース実施し、燃焼時 の系内の燃焼挙動と圧力変化を把握した。なお、試験条件は表3の通りである。

初期温度	水素濃度	メタン濃度		初期温度	水素濃度	メタン濃度
[°C]	[%]	[%]		[°C]	[%]	[%]
25	10	0			10	0
	10	1			10	1
	10	2			10	2
	15	0		75	15	0
	15	1			15	1
	15	2			15	2
	20	0			20	0
	20	1			20	1
	20	2			20	2

表3 試験条件

4.2.3 試験結果と考察

①水素燃焼試験

球状のデフラグレーションの伝播の様子を示したのが図18(上部)である。ここで、初期温度は 25℃、初期圧力は1気圧、水素濃度は10 vol%であり、メタン濃度は0 vol%である。点火後0.1 ms のシュリーレン画像、及び火炎半径 r_b = 2 cm、4 cm、6 cm、8 cm、10 cm のときの画像が示され ている。火炎半径の増加と共に火炎面にセルが形成され、それが発達して複雑な形状になる様 子が観察されている。このセルの形成は予混合火炎の固有不安定性に起因するものである[4]。 また、球状の火炎が全体として上方へ移動することが確認される。これは浮力によるものであり、 燃焼速度が小さい予混合火炎で顕著に現れる挙動である。本試験では、口径30 cm の観察窓を 有する燃焼容器を用いていることから、この条件下での浮力の影響を示すことが出来ている。燃 焼現象を把握するには、十分広い観察窓を有する燃焼容器を用いる必要がある。

容器内の圧力変化を示したのが図18(下部)である。燃焼反応が進行すると共に、容器内圧力 は急激に上昇する。燃焼反応が完了した後、圧力は降下する。これは、燃焼容器から周囲への 熱損失により既燃ガス温度が低くなるからである。なお、図中の火炎半径が最も大きいとき、容器 内圧力は初期圧力より 1 割程度高くなっている[5]。つまり、火炎を可視化した図(上部の図)は、 圧力が上昇しきる前の時間帯のものである。

初期温度が 25°C、水素濃度が 15 vol% と 20 vol% のときのシュリーレン画像を示したのが、図 19と図20の上部である。水素濃度が高くなると共に、火炎の伝播速度は増大している。これは 予混合火炎の燃焼速度が大きくなるからである[6]。また、容器内の最大圧力は上昇する(図19と 図20の下部参照)。これは断熱火炎温度が高くなるからである[7]。なお、水素濃度 20 vol% にお ける燃焼後の圧力変化が大きいのは、火炎温度が高いため周囲への熱損失が大きくなるからで ある。

初期温度が 75℃、水素濃度が 10 vol%、15 vol%、20 vol% のときのシュリーレン画像を示したの が、図21から図23の上部である。初期温度が高くなると、火炎の伝播速度は増大する。これは 反応速度が増大し、燃焼速度が大きくなるからである。また、火炎面の凹凸は滑らかになっている。 これは固有不安定性のレベルが低下するからである。さらに、容器内の最大圧力は、水素濃度が 低いとき上昇し、水素濃度が高いとき下降する(図21から図23の下部参照)。これは、燃焼時に おける周囲への熱損失によるものである[8]。

16



t=0.1ms , rb=0.25cm



t=29.8ms , rb=2cm



t=71.4ms , rb=4cm



t=102.5ms , rb=6cm



t=126.8ms, rb=8cm



t=146.7ms , rb=10cm



図18 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 10 vol%、メタン濃度 0 vol%)



t=0.1ms , rb=0.21cm



t=6.7ms , rb=2cm



t=14.1ms , rb=4cm



t=20.1ms , rb=6cm



t=25.7ms , rb=8cm



t=30.9ms , rb=10cm



図19 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 0 vol%)



t=0.1ms , rb=0.21cm



t=2.9ms , rb=2cm



t=6.0ms, rb=4cm



t=8.6ms , rb=6cm



t=10.9ms , rb=8cm



t=13.1ms , rb=10cm



図20 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 20 vol%、メタン濃度 0 vol%)



t=0.1ms , rb=0.26cm



t=21.4ms , rb=2cm



t=49.0ms , rb=4cm



t=72.2ms , rb=6cm



t=93.5ms , rb=8cm



t=114.1ms , rb=10cm



図21 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 10 vol%、メタン濃度 0 vol%)





図22 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 0 vol%)



t=0.1ms , rb=0.24cm



t=1.9ms , rb=2cm



t=3.8ms , rb=4cm



t=5.5ms, rb=6cm



t=7.0ms , rb=8cm



t=8.4ms , rb=10cm



図23 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 20 vol%、メタン濃度 0 vol%)

②混合気体燃焼試験

初期温度が 25℃、水素濃度 10 vol%、メタン濃度 1 vol%、2 vol% におけるデフラグレーションの シュリーレン画像と容器内圧力変化を示したのが図24(メタン濃度 1 vol%)と図25(メタン濃度 2 vol%)である。ここで、混合気体の当量比は、メタン濃度 0 vol%、1 vol%、2 vol% において、それぞ れ、0.265、0.375、0.487 である。メタン濃度が高くなると共に、火炎の伝播速度は増大し、容器内 の最大圧力は上昇する。前者は予混合火炎の燃焼速度が大きくなることによるもので、後者は断 熱火炎温度が高くなることによるものである。

水素濃度が 15 vol% のときの試験結果を示したのが図26(メタン濃度 1 vol%)と図27(メタン濃 度 2 vol%)である。ここで、混合気体の当量比は、メタン濃度 0 vol%、1 vol%、2 vol% において、それ ぞれ、0.420、0.539、0.660 である。また、水素濃度が 20 vol% の試験結果を示したのが図28(メタ ン濃度 1 vol%)と図29(メタン濃度 2 vol%)である。ここで、混合気体の当量比は、それぞれ、0.595、 0.723、0.855 である。メタン濃度が高くなると共に、火炎の伝播速度は増大する。これは混合気の 当量比が高くなり、予混合火炎の燃焼速度が大きくなるからである。

初期温度が 75℃、水素濃度が 10 vol%、15 vol%、20 vol% のときのシュリーレン画像を示したの が、図30から図35の上部である。初期温度が高くなると、火炎の伝播速度は増大する。また、容 器内の最大圧力は、水素濃度が低いとき上昇し、水素濃度が高いとき下降する(図30から図35 の下部参照)。これらの傾向は、初期温度が 25℃の場合と同様である。

図36は、初期温度が 25°Cのときの容器内の最大圧力を示したものである。水素濃度及びメタ ン濃度が高くなると共に、単調に上昇する。最大圧力の上昇は、水素爆発による破壊力を強める ことに直結するものである。初期温度が 75°Cのときの容器内の最大圧力を示したのが図37であ る。また、表4は、初期温度が 25°C、75°Cのときの容器内の最大圧力を示している。本試験では、 1 ケースあたり3 回の試験を行っており、表4に示した最大圧力は平均値である。それゆえ、図18 から図35に示した最大圧力と若干の違いが生じている。初期温度が高くなると、容器内の最大圧 力は、水素濃度が低いとき上昇し、水素濃度が高いとき下降する。これは、燃焼時間が長いと熱 損失が増大することによるものである[8]。

23



t=0.1ms , rb=0.26cm



t=17.2ms , rb=2cm



t=37.5ms , rb=4cm



t=53.3ms , rb=6cm



t=66.5ms , rb=8cm



t=77.8ms , rb=10cm



図24 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 10 vol%、メタン濃度 1 vol%)



t=0.1ms , rb=0.25cm



t=11.1ms , rb=2cm



t=24.3ms , rb=4cm



t=34.6ms , rb=6cm



t=43.4ms , rb=8cm



t=51.0ms , rb=10cm



図25 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 10 vol%、メタン濃度 2 vol%)



t=0.1ms , rb=0.25cm



t=5.7ms , rb=2cm



t=12.0ms , rb=4cm



t=17.0ms , rb=6cm



t=21.7ms , rb=8cm



t=26.0ms , rb=10cm



図26 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 1 vol%)



t=0.1ms , rb=0.25cm



t=4.0ms, rb=2cm



t=8.4ms , rb=4cm



t=12.0ms , rb=6cm



t=15.3ms , rb=8cm



t=18.2ms , rb=10cm



図27 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 2 vol%)



t=0.1ms , rb=0.25cm



t=2.8ms, rb=2cm



t=5.5ms , rb=4cm



t=7.8ms , rb=6cm



t=9.9ms, rb=8cm



t=11.9ms , rb=10cm



図28 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 20 vol%、メタン濃度 1 vol%)



t=0.1ms , rb=0.25cm



t=2.2ms , rb=2cm



t=4.5ms, rb=4cm



t=6.4ms , rb=6cm



t=8.1ms, rb=8cm



t=9.8ms , rb=10cm



図29 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 25℃、初期圧力 1 気圧、水素濃度 20 vol%、メタン濃度 2 vol%)



t=42.7ms , rb=6cm

t=54.9ms , rb=8cm



t=66.6ms , rb=10cm



図30 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 10 vol%、メタン濃度 1 vol%)



t=0.1ms , rb=0.29cm



t=7.7ms , rb=2cm



t=16.3ms , rb=4cm



t=23.5ms , rb=6cm



t=30.0ms , rb=8cm



t=36.2ms , rb=10cm



図31 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 10 vol%、メタン濃度 2 vol%)



t=0.1ms , rb=0.24cm



t=4.3ms , rb=2cm



t=8.9ms , rb=4cm



t=12.7ms , rb=6cm



t=16.3ms , rb=8cm



t=19.7ms , rb=10cm



図32 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 1 vol%)



t=9.1ms , rb=6cm

t=11.7ms , rb=8cm



t=14.2ms , rb=10cm



図33 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 2 vol%)



t=6.4ms , rb=6cm

t=8.2ms , rb=8cm

t=10.0ms , rb=10cm



図34 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 20 vol%、メタン濃度 1 vol%)





t=3.8ms , rb=4cm



t=5.5ms , rb=6cm



t=7.0ms , rb=8cm



t=8.4ms , rb=10cm



図35 デフラグレーションのシュリーレン画像と容器内圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 20 vol%、メタン濃度 2 vol%)



図36 容器内の最大圧力 (初期温度 25°C、初期圧力 1 気圧、水素濃度 10~20 vol%、メタン濃度 0~2 vol%)



図37 容器内の最大圧力 (初期温度 75℃、初期圧力 1 気圧、水素濃度 10~20 vol%、メタン濃度 0~2 vol%)

初期温度 [℃]	水素濃度 [%]	メタン濃度 [%]	最大圧力 [k P a]	初期温度 [℃]	水素濃度 [%]	メタン濃度 [%]	最大圧力 [k P a]	
25	10	0	305.1	75	10	0	351.1	
	10	1	370.7		10	1	420.5	
	10	2	436.4		10	2	499.7	
	15	0	466.3		15	0	466.4	
	15	1	530.4		15	1	530.8	
		15	2	583.7		15	2	586.3
	20	0	592.5		20	0	565.8	
	20	1	640.0		20	1	615.2	
	20	2	695.3		20	2	664.8	

表4 容器内の最大圧力(初期温度 25℃、75℃)

東京電力福島第一原子力発電所の水素爆発における3号機3階天井部の梁の損傷に関して、 大梁とその周囲の床板に 300~500kPa(ゲージ圧)程度の圧力が 20~40ms 程度の間作用する と、大梁に観察された変形と同程度の変形が生じうるとの報告がある[1]。本試験で得られた結果 (図38、図39)と中間取りまとめに記載されている解析結果には、整合性が有るものと考えられ る。



図38 容器内の最大圧力(初期温度 75℃)



図39 容器内の圧力変化 (初期温度 75℃、初期圧力 1 気圧、水素濃度 15 vol%、メタン濃度 1 vol%)

5. 最新の知見

水素及び混合気体燃焼に関する最新知見を収集し、拡散燃焼及び予混合燃焼に関する知見を 整理した。それらは、以下の通りである。

5.1 最新知見の論文リスト

水素/可燃性有機ガス拡散燃焼

(噴流)

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(対向流)

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(層流)

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(乱流)

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水素/可燃性有機ガス/空気予混合燃焼

(燃焼速度)

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(超音速)

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(動的挙動)

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(球状火炎)

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5.2 論文の概要

水素/可燃性有機ガス拡散燃焼

(噴流)

1.

The effects of hydrogen addition on the stability limits of methane jet diffusion flames

The flame stability limits of confined jet diffusion flames (JDFs) flowing into a co-axial oxidizing stream was studied both experimentally and analytically. Methane and hydrogen and their mixtures were used as the fuel. The experiments were conducted with two different jet diameters and within a wide range of co-flowing stream velocities and hydrogen concentrations in methane or air stream.

The hydrogen diffusion flame was found to have a much larger region of stable operation than the methane JDF. Higher stability of the methane JDFs was achieved by the addition of hydrogen to either the jet fuel or the surrounding air stream. A hysteresis phenomena were observed in the reattachment process of lifted flames. It was found that the conditions prior to ignition of the flame, such as the value of co-flowing stream and jet velocities and position of the ignitor, have significant effect on the type of flame stabilization mechanism and flame blowout limits. The optimum ignition conditions for achieving higher blowout limits were investigated. The blowout limits of lifted JDFs were significantly affected by the velocity of co-flowing stream. The present study also reports the results of the calculation of the blowout limits of lifted JDFs using as a criterion the ratio of mixing time scale to characteristic combustion time scale. The agreement of the experimental and calculated data was satisfactory.

2.

Effects of hydrogen addition to methane on the flame structure and CO emissions in atmospheric burners

Hydrogen addition to methane will have an important role to reach a fully developed hydrogen economy. The effects of this addition on the flame structure and CO emissions were evaluated in two different atmospheric burners. Four fuels with the following composition were used: 100%CH4, 2%H2+98%CH4, 6%H2+94%CH4 and 15%H2+85%CH4. In a single-port atmospheric burner, a decreasing trend in the height of the blue cone with hydrogen addition was determined. The increase in the laminar burning velocity was identified as the main effect on the behavior of this parameter. In a drilled-port atmospheric burner, a significant reduction in CO emissions with hydrogen addition was achieved under two operating conditions: (1) keeping the primary air ratio constant and (2) keeping the primary air ratio and the thermal input constant. The results obtained were consistent with previous experimental studies. This reduction is attributed to a higher concentration of OH radicals as a result of hydrogen addition.

3.

Emission and heat transfer characteristics of methane-hydrogen hybrid fuel laminar diffusion flame

The effect of adding hydrogen to methane on the emission and heat transfer characteristics of a laminar diffusion flame was investigated. The total input thermal energy for each test was kept constant. The results showed that adding hydrogen increased the temperature, decreased the flame length, and significantly increased the soot-free length fraction. CO and CO2 emission decreased with the addition of hydrogen. The more efficient oxidation of CO to CO2 at higher hydrogen fractions was the main contributor to the reduction of CO, whereas decreased carbon input was the dominant factor for the reduction of CO2. The NOx emission increased owing to the increase of prompt, thermal NOx formation and NNH pathway. The ratio of radiative heat flux to total heat flux decreased, and the radiative heat flux did not exceed 5% of the total heat flux. The addition of hydrogen improved the total heat flux by approximately 20%.

Experimental study on the effects of hydrogen addition on the emission and transfer characteristics of laminar methane diffusion flames with oxygen-enriched air

The effects of hydrogen addition on the emission and heat transfer characteristics of oxygenenriched laminar methane diffusion flames were investigated in a laboratory-scale furnace with a co-axial burner. The volume fraction of hydrogen in the methane-hydrogen blend was varied from 0% to 50%, and the oxygen concentration was varied from 25% to 35%. Results showed that the addition of hydrogen led to an increase in the soot-free length and flame temperature while the degree of increase was less at higher oxygen concentrations. Adding hydrogen chemically enhanced the oxidation of CO to CO2, and this chemical effect was stronger when the oxygen concentration increased. NOx emissions increased significantly with the addition of hydrogen, while the rate of this increase decreased with greater oxygen concentrations. The total heat flux increased with the addition of hydrogen, while the rate of this increase was less at higher oxygen concentrations. Although the radiative heat flux increased with higher oxygen concentrations, it did not exceed 6% of the total heat flux at 35% O2. Moreover, adding hydrogen decreased the radiative heat flux; this decrease was significant at higher oxygen concentrations.

5.

Effect of hydrogen enrichment on combustion characteristics of methane swirling and nonswirling inverse diffusion flame

Influence of hydrogen addition on appearance of swirling and non-swirling inverse diffusion flame (IDF) along with emissions characteristics are investigated experimentally. The combustion characteristics including flame length, axial and radial temperature variation, and noise level are analyzed for hydrogen addition in methane by mass basis for constant energy input and by volume basis for constant volumetric fuel flow rate. Hydrogen addition in methane IDF produces shorter flame by compressing entrainment zone, mixing zone, reaction zone, and post-combustion zone. Hydrogen addition shift these zones towards fuel and air exit from the burner. Enrichment of methane with hydrogen on a mass basis up to 6% reduces CO emission considerably and increases NOx emission moderately. Effect of H2 addition on combustion and emission characteristics is more prominent in nonswirling IDF. Combustion noise is augmented with the hydrogen addition and the magnitude of sound level depends on the hydrogen concentration.

6.

Effects of hydrogen enrichment of methane on diffusion flame structure and emissions in a back-pressure combustion chamber

In the present study, the effects of hydrogen enrichment of methane are investigated numerically from the diffusion flame structure and emissions aspect. Fluent code is utilized as the simulation tool. In the first part of the study, four experiments were conducted using natural gas as fuel. A non-premixed burner and a back-pressure boiler were utilized as the experimental setup.

The natural gas fuel consumption rate was changed between 22 Nm3/h and 51 Nm3/h. After the experimental studies, the numerical simulations were performed. The non-premixed combustion model with the steady laminar flamelet model (SFM) approach was used for the calculations. The methane-air extinction mechanism was utilized for the calculation of the chemical species. The numerical results were verified with the experimental results in terms of the flue gas emissions and flue gas temperature values. In the second part of the study, four different hydrogen-enriched methane combustion cases were simulated using the same methane-air extinction mechanism, which included the hydrogen oxidation mechanism as a sub mechanism. The same energy input (432 kW) was supplied into the boiler for all the studied cases. The obtained results show that the hydrogen addition to methane significantly change the diffusion flame structure in the combustion chamber. The hydrogen-enriched flames become broader and shorter with respect to the pure methane flame. This provides better mixing of the reactants and combustion products in the flame regions due to the use of a back-pressure boiler. In this way, the maximum flame temperature values and thermal NO emissions are reduced in the combustion chamber, when the hydrogen addition ratio is less than 15% by mass. The maximum temperature value is calculated as 2030 K for the case with 15% hydrogen addition ratio by mass, while it is 2050 K for the case without hydrogen enrichment. Therefore, it is determined that the hydrogen-enriched methane combustion in a back-pressure combustion chamber has the potential of reducing both the carbon and thermal NO emissions.

(対向流)

7.

Second-law thermodynamics analysis on non-premixed counterflow methane flames with hydrogen addition

Natural gas is an attractive alternative fuel because of its environment-friendly nature, and hydrogen addition is considered as an efficient method to improve the methane combustion performance in combustion engines. In this study, the exergy destruction characteristics in non-premixed counterflow methane flames are numerically studied based on the second law of thermodynamics. The irreversible processes during combustion, such as heat conduction, mass diffusion and chemical reactions, are studied, and it is found that heat conduction is the dominant factor in exergy destruction. Additionally, the exergy destruction from each source shows two peaks, and their overall impact causes the total exergy destruction to exhibit three peaks. Moreover, the effects of hydrogen addition on exergy destruction from heat conduction is insignificant, and the exergy destruction from mass diffusion increases with hydrogen addition. For the exergy destruction from chemical reactions, the carbon-containing reactions are key to the first peak of the exergy destruction rate, whereas the H2-O2 system reactions are more important for the second peak. The contribution of chemical reactions to the overall exergy destruction decreases

with H2 addition.

8.

Experimental investigation of the effect of hydrogen addition on the sooting limit and structure of methane/air laminar counterflow diffusion flames

The influence of hydrogen (H2) addition on the sooting limit and structure of methane/air laminar counterflow diffusion flames has been studied. Soot limits have been obtained using the laser light scattering technique for CH4/H2 mixtures with H2 concentration varying from 0–20% by volume in the fuel mixture for different strain rates. The resulting soot limit map shows a significant increase in the fuel concentration at the soot limit with increasing amounts of H2. To understand this trend, temperature and species concentration profiles have been measured and compared under the influence of H2 addition in (a) an incipiently sooting and (b) in a sooting CH4/air flame. Flame temperatures have been measured using a thin-wire S-type thermocouple and species profiles have been measured using the gas chromatography technique (GC). The results indicate a significant decrease in the amounts of higher hydrocarbons such as benzene and naphthalene (which are considered important soot precursors) with an increase in H2 concentration for the sooting flame. To explain this decrease in the concentration of higher hydrocarbons, pathway analysis has been performed to elucidate the influence of H2 on the formation and consumption of soot forming species.

9.

Combined experimental and numerical study on the extinction limits of non-premixed H2/CH4 counterflow flames with varying oxidizer composition

Chemical reaction mechanisms with detailed kinetics are an important topic in combustion science and an essential prerequisite for the accurate modeling of reactive flows in combustors. Besides isolating and studying individual reactions, the development of reaction mechanisms is often based on well-defined experimental observables, such as the laminar burning velocity and the ignition delay time. While many optimization targets are associated with premixed combustion, the extinction strain rate (ESR) of non-premixed flames in the counterflow configuration is another well-defined experimental observable which, however, often receives less attention. In order to reduce the scarcity of corresponding datasets for the emerging fuel hydrogen and its blends with methane, this work reports ESR measurements for H2, CH4/H2 and CH4 counterflow diffusion flames considering a variation of the oxygen content in the oxidizer stream between 14 % and 21 %. The experimental investigation is complemented by calculations with a 1D counterflow model utilizing a temperature-control continuation method in order to determine the extinction limits numerically. The simulations are performed with six different well-established chemical reaction mechanisms. It is shown from both, experimental and numerical results, that with the substitution of CH4 by H2 the ESR increases and further, that the ESR decreases with a reduction of the oxygen content in the oxidizer stream. In addition, decreasing flame temperatures are observed at extinction as the H2 content increases. Overall, all mechanisms are able to qualitatively recover

the trends found for varying H2 contents, fuel mole fraction, and oxygen content in the oxidizer. However, significant quantitative deviations are observed between the numerical results regarding the ESR values and the deviations are larger than for other important flame characteristics, such as the laminar burning velocity. The results suggest that the ESR could be a useful optimization target for further improving chemical reaction mechanisms which underlines the importance of datasets such as the one presented in this work.

10.

Machine learning techniques to predict the flame state, temperature and species concentrations in counter-flow diffusion flames operated with CH4/CO/H2-air mixtures

The usage of artificial intelligence (AI) is increasing in many fields of research, since complex physical problems can be 'learned' and reproduced by AI methods. Thus, instead of numerically solving partial differential equations, describing the physical processes in detail, appropriate AI methods can be used to decrease the calculation time significantly. In the present study, artificial neural networks (ANNs) were used to predict temperature and species concentrations in a laminar counter–flow diffusion flame. To improve the accuracy of the ANNs, a support vector machine (SVM) was used to subdivide the wide range of operating conditions (air–fuel ratio, strain rate, fuel mixture) into 'flame' and 'no flame' cases. Due to classification with the SVM the prediction performance of the ANNs was optimized and an average error to the reference values (GRI3.0) below 10 K for all cases was detected, whereas the calculation time was decreased by a factor of about 4,800 (solving the transport equations with GRI3.0).

(層流)

11.

Preferential diffusion effects on NO formation in Methane/Hydrogen-air diffusion flames

A numerical study in methane/hydrogen diffusion flames has been conducted to clarify the preferential diffusion effects of H2 and H with detailed chemistry. The composition of fuel is systematically changed from pure methane to pure hydrogen through the molar addition of H2 to methane. A comparison was made by employing three species diffusion models, i.e., mixture–averaged species diffusion and the suppression of the diffusivities of H and H2. The behavior of maximum flame temperatures with the three species diffusion models is not explained by the scalar dissipation rate but the nature of chemical kinetics such as the behaviors of chain carrier radicals of H, O, and OH. It is found that the preferential diffusion of H radical into the reaction zone curbs the populations of the chain carrier radicals and then flame temperature while that of H2 into the reaction zone produces the reduction of the scalar dissipation rate and the population of chain carrier radicals and these force the flame temperature to decrease. These preferential diffusion effects of H2 and H are also compared among NO emission behaviors through the three species diffusion models. Under all flame conditions, Fenimore NO is much more remarkable compared to thermal NO. It is also seen that the preferential diffusion of H radical into the reaction zone

suppresses the thermal and Fenimore NO while that of H2 into the reaction zone increases them. To facilitate the details of those NO behaviors through preferential diffusion effects of H2 and H, importantly contributing reaction steps to the production and destruction of Fenimore NO are addressed.

12.

Flame base structures of micro-jet hydrogen/methane diffusion flames

In this study, a comparison of flame base structures of hydrogen/methane-air diffusion flames formed over a tiny-jet is made numerically for both isothermal and thermal conductive burner conditions, in order to clarify the fuel dependent flame stabilization mechanisms. It is found that, unlike a methane flame, the flame base of a hydrogen flame always attaches to the burner. The analyses indicate that the dominant intermediate-consumption steps have significantly lower activation energies for the hydrogen flame as compared to a methane flame. More importantly, one of the HO2 production reactions (R43f: H + O2 + M \rightarrow HO2 + M), which has a dominant role in sustaining reactivity at the flame base, shows a negative temperature dependence, causing the heat release rate in the flame base kernel to increase as the burner wall temperature decreases. With a thermal conductive burner (thermal conductivity of 16 W/m-K) over a wide range of fuel jet velocities (0.5-4.0 m/s), it is found that the burner tip is heated to a significantly higher temperature by a hydrogen flame due to its unique stabilization mechanism. The mixing effects of hydrogen and methane are then considered. It is found that the burner tip temperature can be reduced by adding methane into the fuel flow. This is because, according to the investigation of the structures of the hydrogen/methane jet diffusion flames, the reaction rate of R43f is suppressed due to the included intermediates (e.g., CH3, CH2O) consumption steps of methane. It is expected that the flame attachment feature associated with the flame base structure can be easily controlled by mixing hydrogen and methane, making it possible to control the burner tip temperature in advance.

13.

Experimental characterization of diffusive-thermal instabilities in CO2-diluted H2-CH4-CO unstrained diffusion flames

The combustion of multi-fuel mixtures is experimentally studied for the first time in unstrained diffusion flames, where the parasitic hydrodynamic effects present in common research burners are negligible. A broad range of H2-CO-CH4 fuels highly diluted in CO2 is investigated to provide an understanding of the intrinsic diffusive-thermal instabilities (DTIs) that onset in low calorific biomass-derived syngas. For each fuel blend, the burning intensity or the Damköhler number (Da) is gradually reduced, going through the marginal stability state where DTIs first appear, down to the lean extinction limit. Flame stability limits are provided. From the large difference between the Lewis numbers of the multiple fuel species (Lei), the cells that onset due to H2 are seen to interact and compete with the pulsations from CO and CH4, leading to superimposed cellular-pulsating instabilities. These are thoroughly characterized by measuring the pulsations amplitude, frequency,

cell size, number of cells, and fraction of the flame sheet actively burning. An effective fuel Lewis number (Le F,eff) calculated from the fuel mixture composition is introduced and used along with the Damköhler number to map the DTIs observed. At lower Le F,eff and D a , the cellular attributes of the superimposed instabilities dominate, while at larger Lewis numbers and the near marginal stability state, pulsations prevail.

14.

Study on behavior and emission of methane/hydrogen diffusion flame with applied DC electric field

This experimental study investigates the effect of DC electric fields on flame behavior and emissions in non-premixed hydrogen/methane flames using a co-flow burner. The study considers varying hydrogen mole fractions of 0.1, 0.3, and 0.5, and different fuel flow velocities of 2.0, 6.3, and 8.0 cm/s. To introduce DC electric fields, a high voltage terminal was connected to the fuel nozzle, while the ground terminal was connected to an upper mesh located above the flame. The applied DC voltages ranged from Vdc = -10 kV to +10 kV. The study reveals that the addition of hydrogen reduces flame height. Furthermore, when subjected to DC electric fields, the flames exhibit movement towards the lower potential side, displaying stable and oscillating behaviors due to the Lorentz force acting on positive ions within the flames. The concentrations of CO and CO2 exhibit insignificant changes with varying hydrogen mole fractions. However, when exposed to positive voltage, CO, CO2, and NOX emissions are reduced. This research provides a detailed analysis of flame/flow behavior and emission characteristics when hydrogen and DC electric fields are introduced, providing valuable insights into the control of flame behavior and pollutant emissions.

(乱流)

15.

Application of a reduced mechanism by computational singular perturbation method to the calculation of the ignition delays of turbulence diffusion flame CH4/H2/N2

This work presents an application of a reduced chemical kinetic mechanism using computational singular perturbation (CSP) based on the significant indices of the modes on the evolution of species and the degree of participation of reactions. With this approach, the mechanism of Yang and Pope is reduced to 22 reversible reactions (RR22). In this study, the tabulation of ignition delays is made with Yang and Pope mechanism, GRI 3.0, and the reduced mechanism RR22; the results obtained show a good agreement among the three mechanisms. The "Modèle Intermittent Lagrangien" (MIL) necessary to calculate the chemical source term of the transport equation of the species requires the library of ignition delays determined above and a probability density function (PDF) of the mixture fraction presumed by a beta distribution. The scalar variance, one of the key parameters for the determination of the presumed beta function, is obtained by solving its own transport equation with the unclosed scalar dissipation rate modeled

using either an algebraic model or a transport equation. All these models are introduced in the computational fluid dynamics "Code-Saturne" to simulate a turbulent CH4/H2/N2 jet flame (DLR Flame A) performed at the Deutsches Zentrum für Luft-und Raumfahrt (DLR), or German Aerospace Center. A set of comparisons is made and the results of simulations show a good agreement among the three mechanisms as well with the experimental data. 16.

CFD modellimg of a turbulent CH4/H2/N2 jet diffusion flame with detailed chemistry

A CFD model based on the Reynolds Averaged Navier-Stokes (RANS) approach combined with a detailed chemical kinetic mechanism to investigate a turbulent CH4/H2/N2 jet diffusion flame is developed. The CFD governing equations of momentum, mass, and energy in the turbulent field were solved in conjunction with the standard k- ε turbulence model. The laminar flamelet concept that views the turbulent diffusion flame as an ensemble of laminar diffusion flamelets is adopted. The coupling between turbulence and chemistry is achieved by the statistical description of three parameters namely (1) mixture fraction (Z), (2) variance of mixture fraction (Z"2) and (3) scalar dissipation rate (χ). The flamelet model consists of two steps namely (a) the generation of a set of laminar flamelet solutions and (b) the integration of the laminar flamelet solutions with presumed-shape Probability Density Function (PDF). The GRI Mech-3.0 mechanism that involves 53 species and 325 reactions is adopted. The effect of various parameters such as C1 arepsilon constant in the turbulent dissipation transport equation on the numerical solution is highlighted. Also, the comparison between the CFD model results and the experimental data of velocity, temperature and mass fractions of species (CH4, H2, N2, H2O, CO2, O2 and CO) along the centreline as well as on the radial position of x/D = 5, 40 are presented. Generally, the CFD results show a good agreement with the experimental data, and the presented approach in this paper is an accurate promising alternative to LES and DNS approaches for the modelling of non-premixed turbulent configurations.

水素/可燃性有機ガス/空気予混合燃焼

(燃焼速度)

17.

Burning velocity and Markstein length blending laws for methane/air and hydrogen/air blends

Because of the contrasting chemical kinetics of methane and hydrogen combustion, the development of blending laws for laminar burning velocity, ul, and Markstein length for constituent mixtures of CH4/air and H2/air presents a formidable challenge. Guidance is sought through a study of analytical expressions for laminar burning velocity. For the prediction of burning velocities of blends, six blending laws were scrutinized. The predictions were compared with the measured burning velocities made by Hu et al. under atmospheric conditions [1]. These covered equivalence ratios ranging from 0.6 to 1.3, and the full fuel range for H2 addition to CH4. This enabled

assessments to be made of the predictive accuracy of the six laws. The most successful law is one developed in the course of the present study, involving the mass fraction weighting of the product of ul, density, heat of reaction and specific heat, divided by the thermal conductivity of the mixture. There was less success from attempts to obtain a comparably successful blending law for the flame speed Markstein length, Lb, despite scrutiny of several possibilities. Details are given of two possible approaches, one based on the fractional mole concentration of the deficient reactant. A satisfactory empirical law employs mass fraction weighting of the product ulLb. 18.

Laminar flame speed of H2/CH4/air mixtures with CO2 and N2 dilution

The laminar flame speeds of H2/CH4/air mixtures with CO2 and N2 dilution were systematic investigated experimentally and numerically over a wide range of H2 blending ratios (75 vol%) with CO2 (67 vol%) and N2 (67 vol%) dilution in the fuels. The experimental measurements were conducted via the Bunsen flame method incorporating the Schlieren technique under the condition of equivalence ratios from 0.8 to 2.0. To gain an insightful understanding of the experimental observations, detailed numerical simulation was carried out using Chemkin-Pro with GRI3.0-Mech. The experimental measurements were also used to validate the corresponding performance of a semiempirical correlation derived through asymptotic analysis method coupled with the reduced chemistry mechanism. The results showed that at lower H2 fraction (xH2 \leq 0.5), the laminar flame speeds of H2/CH4/air mixtures displayed great linearly increase with the growth of H2 fractions. The combustion of mixtures with low H2 contents was dominated by CH4 conversion which was mainly controlled by the increasing OH radicals produced from the key oxidation reactions of H +O2 = O + OH. With the further increase of H2 fractions, the methane-dominated combustion gradually transformed into the methane-inhibited hydrogen combustion, resulting to the growth of laminar flame speeds was dramatical and non-linear. Due to the larger heat capacity and chemical kinetic effect, CO2 presented a stronger dilution effect on reducing the laminar flame speeds than N2. With the addition of CO2, the increasing stronger competition for H radical through CO + OH = CO2 + H with H + O2 = O + OH due to the significant reduction of H mole fractions, leading to the larger decrease of laminar flame speeds of mixtures. Besides, although the contribution of thermal effect of CO2 decreased near the equivalence ratio, the thermal effect of CO2 still preformed the dominated contribution to the total dilution effect. A comparison between the experimental data and estimated results using the semiempirical correlation showed that, the correlation using new modified coefficients provided the satisfactorily accuracy predictions on the laminar flame speeds of diluted H2/CH4/air mixtures at lower xH2 (xH2 \leq 0.5) and lower xdilution (xdilution = 0.25). The estimated results were generally located within a deviation range of $\pm 20\%$ errors except for two unsatisfactory eases occurred at conditions of xH2 = 0.75 and xCO2 = 0.67. The considerably poor predictions were attributed to the significantly variation of the chemical kinetics under high H2 content and large CO2 dilution conditions.

19.

Experimental and numerical assessment of the effects of hydrogen admixtures on premixed methane-oxygen flames

Thermal utilization of hydrogen is becoming increasingly important as the climate change progresses. Fossil fuels such as natural gas are replaced by green hydrogen in the natural gas grid to reduce CO2 emissions. However, the switch to hydrogen causes significant changes in combustion properties, such as higher flame temperatures or higher burning velocities. As a result, this change in flame properties impacts application processes. In order to prevent a reduction in quality, the processes must be optimally adapted to the fuel switch. Therefore, the combustion properties of the gas mixture have to be investigated in more detail. In this work a premixed oxyfuel combustion of hydrogen-methane mixtures under atmospheric conditions has been investigated. Therefore, two scenarios are of further interest, low hydrogen admixture (0 vol-%, 10 vol-%, 20 vol-%, and 35 vol-%) and high hydrogen admixture (50 vol-%, 75 vol-%, 95 vol-%/100 vol-%). In this study, a premixed burner is utilized at three different burner powers with a maximum power of 1.2 kW. The flame characteristics has been analyzed by optical (chemilumicence and OH-PLIF), spectroscopic, and thermal measurements. This study aims to determine the change in flame shape, the temperature profiles at different flame heights, and the species formed in the combustion zone. For this purpose, various compositions of hydrogen-methane-oxygen mixtures at different equivalence ratios $_{\odot}$ = 0.8–1.2 are experimentally investigated at atmospheric conditions. The effect of hydrogen addition to the methane-oxygen flame has been numerically considered utilizing three different mechanisms (GRI 3.0, Glarborg, and Aramco). The adiabatic flame temperature, laminar burning velocity and radical formation have been studied numerically for different gas compositions.

20.

Laminar burning velocities and Markstein numbers for pure hydrogen and methane/hydrogen/air mixtures at elevated pressures

Spherically expanding flame propagations have been employed to measure flame speeds for H2/CH4/air mixtures over a wide range of H2 fractions (30 %, 50 %, 70 and 100 % hydrogen by volume), at initial temperatures of 303 K and 360 K, and pressures of 0.1, 0.5 and 1.0 MPa. The equivalence ratio (ϕ) was varied from 0.5 to 2.5 for pure hydrogen and from 0.8 to 1.2 for methane/hydrogen mixtures. Experimental laminar burning velocities and Markstein numbers for methane/hydrogen/air mixtures at high pressures, which are crucial for gas turbine applications, are very rare in the literature. Moreover, simulations using three recent chemical kinetic mechanism (Version 20161214)) were compared against the experimentally derived laminar burning velocities. The maximum laminar burning velocity for 30 % and 50 % H2 occurs at $\phi = 1.1$. However, it shifts to $\phi = 1.2$ for 70 % H2 and to $\phi = 1.7$ for a pure H2 flame. The laminar burning velocities increased with hydrogen fraction and temperature, and decreased with pressure. Unexpected behaviour was recorded for pure H2 flames at low temperature and $\phi = 1.5$, 1.7 wherein ul did not

decrease when the pressure increased from 0.1 to 0.5 MPa. Although, the measurement uncertainty is large at these conditions, the flame structure analysis showed a minimum decline in the mass fractions of the active species (H, O, and OH) with the rise in the initial pressure. Markstein length (Lb) and Markstein number (Mab and Masr) varied non-monotonically with hydrogen volume fraction, pressure and temperature. There was generally good agreement between simulations and experimentally derived laminar burning velocities, however, for experiments of rich-pure hydrogen at high initial pressures, the level of agreement decreased but remained within the limits of experimental uncertainty.

(乱流)

21.

Effects of hydrogen enrichment on CH4/Air turbulent swirling premixed flames in a cuboid combustor

Effects of H2-enrichment on structures of CH4/air turbulent swirling premixed flames affected by high intensity turbulence in a gas turbine model combustor are investigated by conducting direct numerical simulations. Two stoichiometric mixture conditions, of which volume ratio of CH4:H2 = 50:50 and 80:20, are simulated by considering a reduced chemistry (25 species and 111 reactions). Results showed qualitatively different flame shapes and reaction zone characteristics between the cases. For the higher H2-ratio case, the flame is stabilized both in the inner and outer shear layers. For the lower H2-ratio case, the flame is stabilized only in the inner shear layer and extinction occurs in the outer shear layer. Comparison of the reaction zone characteristics with unstrained and strained laminar flames in phase space showed that H2 mass fraction for the lower H2-ratio case and reaction rate profiles for both cases deviate from the corresponding laminar values. Analysis of fuel species conservation equation suggests that the turbulent transports are substantially influential to determine local and global flame structures. These findings would be useful for designing practical H2-enriched gas turbine combustor in the aspect of flame structures under high intensity turbulence.

22.

Morphology and structure of spherically propagating premixed turbulent hydrogen - air flames

Three-dimensional direct numerical simulations of spherically propagating premixed turbulent stoichiometric hydrogen-air flames with detailed chemistry and detailed diffusion are employed to clarify the influence of turbulence-flame interactions with respect to flame structure and morphology. Four cases are considered within the corrugated flamelets and the thin reaction zone regimes. The most significant fuel consumption and heat release rates occur at the negatively-curved flamelets. Furthermore, the increments in burning velocity are lower than the increments in flame surface area, which is due to the reduction in the local burning intensity at the positively-curved flamelets. The morphology of intense reaction zones is quantified using Minkowski functionals and their shapes include "tubes", "pancakes" and more complex shapes, which are

compared to their counterparts in planar flames. As turbulence level increases, the number of locally defined intense reaction zones increases, and their boundaries expand to cover more extensive parts of the flame front. However, intense reaction zones' geometrical dimensions do not significantly differ for each flame as it propagates. Local turbulence properties are obtained for each intense reaction zone. The conditional averages of local Taylor microscale and local Kolmogorov scale, conditioned based on the shape finders, are investigated. The conditional averages of the local Taylor microscale scale correlate with the planarity and filamentary of intense reaction zones. Therefore, turbulent motions at Taylor microscale size have a significant role in characterizing turbulence-flame interactions relevant to flame morphology and relevant to the local flame thickness and reaction layers of developing-flames. On the other hand, local Kolmogorov scales' turbulent motions show weaker or no such correlations. There is a dissidence between global turbulence statistics and local ones representing the interactions at the flame front. Local turbulence-flame interactions of Taylor microscale sizes occur at specific length scales, depending on the flame size and irrelevant of eddies with other length scales.

(超音速)

23.

Role of chemical kinetics on the detonation properties of hydrogen /natural gas/air mixtures

The first part of the present work is to validate a detailed kinetic mechanism for the oxidation of hydrogen-methane-air mixtures in detonation waves. A series of experiments on auto-ignition delay times have been performed by shock tube technique coupled with emission spectrometry for H2/CH4/O2 mixtures highly diluted in argon. The CH4/H2 ratio was varied from 0 to 4 and the equivalence ratio from 0.4 to 1. The temperature range was from 1250 to 2000K and the pressure behind reflected shock waves was between 0.15 and 1.6MPa. A correlation was proposed between temperature (K), concentration of chemical species (molm-3) and ignition delay times. The experimental auto-ignition delay times were compared to the modelled ones using four different mechanisms from the literature: GRI [Smith PG, Golden DM, Frenklach M, Moriarty NW, Goldenberg M, et al. (http://www.me.berkeley.edu/gri_mech/)], Marinov et al. [Aromatic and polycyclic aromatic hydrocarbon formation in a laminar premixed n–butane flame. Combust Flame 1998; 114:192-213], Hughes et al. [(http://www.chem.leeds.ac.uk/Combustion/Combustion.html)], Konnov [Detailed reaction mechanism for small hydrocarbons combustion. Release 0.5 (http://homepages.vub.ac.be/~akonnov/), 2000]. A large discrepancy was generally found between the different models. Konnov's model, which auto-ignition delay times predictions were the closest to the measured ones, has been selected to calculate ignition delay times in the detonation waves. The second part of the study concerned the experimental determination of the detonation properties, namely detonation velocity and cell size. Effect of the initial composition, hydrogen to methane ratio and the amount of oxygen in the mixture, as well as the initial pressure on the detonation velocity and on the cell size were investigated. The ratio of methane/(methane +

hydrogen) varied between 0 and 0.6 for two different equivalence ratios (0.75 and 1) while the initial pressure was fixed to 10 kPa. A correlation was established between the characteristic cell size and the ignition delay time behind the leading shock of the detonation. It was clearly shown that methane has an important inhibitor effect on the detonation of these combustible mixtures. 24.

Fast-flame limit for hydrogen/methane-air mixtures

Flame acceleration experiments were performed in a 10 cm inner-diameter tube filled with evenly spaced 0.43 blockage ratio orifice plates. The critical mixture composition required for flame acceleration to a fast-flame was measured for four methane/hydrogen fuel-air mixtures at initial temperatures of 298K, 423K, and 573K. These conditions provide a large range in the Zeldovich number between 12 and 28, where the Zeldovich number was calculated from the laminar burning velocity obtained from 1-D flame simulations. The data collapsed very well when the expansion ratio across the flame (calculated at the critical condition) was plotted versus the Zeldovich number. This is consistent with correlation proposed by Dorofeev [7], that was based on experimental data obtained over a narrower Zeldovich number range. For pure hydrogen fuel, the critical expansion ratio was found to be between 2 and 4, and for pure methane the critical expansion ratio was as high as 8, for an initial temperature of 573K.

(動的挙動)

25.

Numerical investigations on flashback dynamics of premixed methane-hydrogen-air laminar flames

Injecting hydrogen into the natural gas network to reduce CO2 emissions in the EU residential sector is considered a critical element of the zero CO2 emissions target for 2050. Burning natural gas and hydrogen mixtures has potential risks, the main one being the flame flashback phenomenon that could occur in home appliances using premixed laminar burners. In the present study, two-dimensional transient computations of laminar CH4 + air and CH4 + H2 + air flames are performed with the open-source CFD code Open FOAM. A finite rate chemistry based solver is used to compute reaction rates and the laminar reacting flow. Starting from a flame stabilized at the rim of a cylindrical tube burner, the inlet bulk velocity of the premixture is gradually reduced to observe flashback. The results of the present work concern the effects of wall temperature and hydrogen addition on the flashback propensity of laminar premixed methane-hydrogen-air flames. Complete sequences of flame dynamics with gradual increases of premixture velocity are investigated. At the flame flashback velocities, strong oscillations at the flame leading edge emerge, causing broken flame symmetry and finally flame flashback. The numerical results reveal that flashback tendency increase with increasing wall temperature and hydrogen addition rate.

Numerical investigation of the hydrogen, ammonia and methane fuel blends on the combustion

^{26.}

emissions and performance

The co-combustion of traditional methane gas and alternative fuels importance to reduce emissions in combustion has increased in recent years. The literature proves the successful operations of ammonia and hydrogen as diesel engine fuels. However, there is not sufficient information about the combustion of methane along with ammonia and hydrogen. In this study, the effects of the combustion of methane-hydrogen and methane-ammonia-hydrogen fuel mixture on system performance and emissions are numerically investigated. Firstly, the effects of methane and 5%, 10%, and 15% hydrogen mixture are investigated. Then, methane and 5% fixed hydrogen ratio with 5% ammonia, 10% ammonia, and 15% ammonia mixtures are examined. The numerical model is validated against the literature data using the Sandia D model with a difference of 5.9% at x/d = 0.5. As a result of the study, 15% hydrogen addition to methane increased the maximum combustion chamber temperature by 100 K. However, with the addition of 15% of ammonia, the temperature is dropped by 200 K and the peak temperature location is slightly shifted away from the injection point. A 10% enhancement of hydrogen content rate will cause a 28% increase in thermal NOX emission and a 10% increment in the ammonia content of the fuel blend has caused to 3000 ppm enhancement in NOX emission. With the addition of %5, 10%, and %15 ammonia mass fraction to methane and hydrogen blend fuel at the axial location of x/d = 0.444, the NOx emission production rate has been increased by 1970, 3010, and 3790 ppm, respectively. In addition, the 15% hydrogen addition to methane (85% methane/15% hydrogen) and 5% hydrogen plus 15% ammonia addition to methane (80% methane/5% hydrogen/15% ammonia) reduced the CO2 emission by 30.7%and 14% compared to neat methane (100% methane) combustion. To sum up, this study shows that the use of methane-ammonia-hydrogen as a diesel engine fuel reduces combustion emissions. 27.

The effect of hydrogen enrichment on thermoacoustic instabilities in laminar conical premixed methane/air flames

We perform a conceptual study about the linear stability of a hydrogen-enriched methane-air premixed laminar flame inside a cylindrical duct with both ends open. The flame and acoustic subsystems are coupled using the Flame Transfer Function (FTF). The power output is set to a constant value and the hydrogen molar fraction of the fuel mixture is varied. We show that adding hydrogen reduces the flame length and impacts the FTF in two ways: (i) gain drop-off shifts towards higher frequencies and (ii) phase lag reduces. Then, we compute the eigenvalues of the thermoacoustic system varying the hydrogen molar fraction. We show that adding hydrogen to the fuel mixture can stabilize linearly unstable systems and vice versa, depending on the duct natural frequencies. The results show that the hydrogen molar fraction can be a tunable parameter for controlling thermoacoustic instabilities. (球状火炎)

28.

Effects of hydrogen concentration on premixed laminar flames of hydrogen-methane-air

The unstretched laminar burning velocities and Markstein numbers of spherically propagating hydrogen-methane-air flames were studied at a mixture pressure of 0.10 MPa and a mixture temperature of 350 K. The fraction of hydrogen in the binary fuel was varied from 0 to 1.0 at equivalence ratios of 0.8, 1.0 and 1.2. The unstretched laminar burning velocity increased non-linearly with hydrogen fraction for all the equivalence ratios. The Markstein number varied non-monotonically at equivalence ratios of 0.8 and 1.0 and increased monotonically at equivalence ratio of 1.2 with increasing hydrogen fraction. Analytical evaluation of the Markstein number suggested that the trends could be due to the effective Lewis number, which varied non-monotonically at 1.2. The propensity of flame instability varied non-monotonically with hydrogen fraction at equivalence ratios of 0.8 and 1.0 and increased monotonically at 1.2. The propensity of flame instability varied non-monotonically with hydrogen fraction at equivalence ratios of 0.8 and 1.0 and increased monotonically at 1.2.

29.

Investigation of cellularization characteristics of hydrogen-methane-ethanol expanding spherical flame at elevated pressures

The incorporation of ethanol into hydrocarbon fuels for use is attracting increasing interest and it is necessary to investigate its inherent flame instability for better application in combustion units. The instability of hydrogen-methane-ethanol spherically expanding flame has been investigated at an initial temperature of 400 K, initial pressures of (2-4 bar), ethanol fraction of (20%, 50%, 80%), and equivalence ratios (Φ) of (0.7–1.4) using the constant volume combustion chamber (CVCC). High-speed schlieren technology was used to record flame propagation images. The effects of hydrodynamic and thermal-diffusion effect on the inherent instability of the flame were investigated. As the ethanol ratio increased, the hydrodynamic effect was enhanced. The thermal-diffusion effect was discovered to stabilize the flame surface under all conditions, as judged jointly by the effective Lewis number and the critical Lewis number. The critical conditions (critical radius and Peclet number) at the onset of instability were evaluated, and it was found that the flames were more prone to flame instability at higher pressures. The critical Peclet number increased with the increase in the equivalence ratio when the ethanol ratio was 20%, and showed the opposite trend when the ethanol ratio was 50% and 80%. In addition, as the ethanol ratio increases, the stability of the lean mixtures flame increases, while the rich mixtures flame suffers from early on- set of instability. The theoretical and experimental results were consistent, with some differences at Φ = 1.4. An empirical correlation formula for the critical Peclet number (Pe c) and Markstein number (M b) was further proposed (Pe c = 18.03 M b + 214.78). Finally, the Karlovitz number was used to study the instability behavior of the flame. The critical Karlovitz number (Ka c) decreased with increasing M b and the tendency of the flame to suffer from instability diminished, and the following correlation was obtained Ka c = $0.05635 \times exp$ (-0.13852

M b). Furthermore, the flame was more unstable in rich mixtures, this was consistent with the conclusion of instability derived from the critical radius.

30.

Effects of hydrogen on combustion characteristics of methane in air

The explosion process of multi-component gas mixture is extremely complex and may cause serious disaster effects. The safety issue concerning explosion of multi-component gas mixture is urgent to be investigated on account of its wide range of applications. In current work, series of experiments were performed in a 20 L spherical explosion vessel at initial conditions of 1 atm and 293 K, involving methane-hydrogen/air mixtures. The proportion of hydrogen in fuels varied from 0% to 100%. It was observed that peak temperature is always behind the peak pressure in arrival time whatever the fuel equivalence is. Experimental values of peak overpressure are lower than adiabatic ones due to heat loss. It was also founded that the hydrogen addition can raise explosion pressure and temperature in experiment but slightly decrease that in adiabatic condition, and both the increase in experiment and the decrease in adiabatic show a linear correlation versus the proportion of hydrogen. Hence the deviation between the experimental results and the adiabatic results decreases as the hydrogen proportion rises. Moreover, the positive effect of hydrogen addition on (dp/dt)max is very slight at low hydrogen proportion, while the effect becomes much more pronounced at higher hydrogen contents, showing an exponential growth. For each fuel composition throughout all experiments, the peak overpressure, peak temperature and (dp/dt)max concerning fuel equivalence ratios of 0.6, 1 and 1.5 follow a same rule: Φ = 1 is the highest, followed by Φ = 1.5 and Φ = 0.6. Finally, the MIEs of gaseous methane-hydrogen/air mixtures at a fuel equivalence ratio of 1.5 were measured as a function of hydrogen proportion. It shows a sharp decrease as the fraction of hydrogen in fuel rises, from 118 mJ for methane-air to 0.12mJ for hydrogen-air. It is also observed that the MIE of multi-component gas mixtures can be approximately figured as the linear weighted sum of the MIE of each component; the weighting factor is respectively the volume fraction of each component. This can be considered as a universal method to obtain the MIE for a specific multi-component gas. 31.

The effect of hydrogen addition on methane/air explosion characteristics in a 20-L spherical device

The addition of hydrogen to methane changes its deflagration characteristics and increases the combustion rate. However, studies on the effect of hydrogen on methane deflagration remain insufficient. Therefore, based on the CFD code GASFLOW-MPI, a four-step combustion-mechanism model was established for methane/hydrogen mixtures. The deflagration characteristics of a premixed combustible gas in a 20-L spherical device was numerically simulated using a methane/hydrogen/air equivalence ratio of 1 and hydrogen addition in the range of 0-50%; subsequently. The results were compared with experimental data. The four-step methane/hydrogen combustion-mechanism could effectively reproduce the methane/hydrogen

deflagration process on considering the heat losses. With an increase in hydrogen addition, the laminar burning velocity increases, and the deflagration duration reduces. It decreases the explosion heat loss and increased the maximum deflagration pressure. Under adiabatic simulation, the maximum deflagration pressure decreased with an increase in hydrogen addition, in contrast with the experimental results. This indicates that the heat-loss effect of the methane/hydrogen/air-mixture deflagration process should not be ignored. Moreover, the heat loss during the methane/hydrogen/air-mixture deflagration and convective heat-transfer mechanisms should be considered in the numerical simulations of methane/hydrogen/air-mixture deflagration.

(長岡技術科学大学)

32.

Outward propagation velocity and acceleration characteristics in hydrogen-air deflagration

Propagation characteristics of hydrogen-air deflagration need to be understood for an accurate risk assessment. Especially, flame propagation velocity is one of the most important factors. Propagation velocity of outwardly propagating flame has been estimated from burning velocity of a flat flame considering influence of thermal expansion at a flame front; however, this conventional method is not enough to estimate an actual propagation velocity because flame propagation is accelerated owing to cellular flame front caused by intrinsic instability in hydrogen-air deflagration. Therefore, it is important to understand the dynamic propagation characteristics of hydrogen-air deflagration. We performed explosion tests in a closed chamber which has 300 mm diameter windows and observed flame propagation phenomena by using Schlieren photography. In the explosion experiments, hydrogen-air mixtures were ignited at atmospheric pressure and room temperature and in the range of equivalence ratio from 0.2 to 1.0. Analyzing the obtained Schlieren images, flame radius and flame propagation velocity were measured. As the result, cellular flame fronts formed and flame propagations of hydrogen-air mixture were accelerated at the all equivalence ratios. In the case of equivalent ratio 0.2, a flame floated up and could not propagate downward because the influence of buoyancy exceeded a laminar burning velocity. Based upon these propagation characteristics, a favorable estimation method of flame propagation velocity including influence of flame acceleration was proposed. Moreover, the influence of intrinsic instability on propagation characteristics was elucidated.

33.

Effects of inert-gas addition on the dynamic behavior and propagation characteristics of spherically expanding hydrogen-air flames

To investigate the effects of inert-gas addition on the dynamic behavior and propagation characteristics of spherically expanding hydrogen-air flames, the experiments of premixed combustion were performed in a closed chamber. The dynamic behavior of premixed flames was caught by high-speed Schlieren imaging, and the flame radius and propagation velocity were

measured by analyzing the Schlieren photography. When the flame radius was sufficiently small, smooth flame surface was observed, where the flame stretch affected strongly the propagation velocity. From the correlation between the propagation velocity and flame stretch rate, we estimated the propagation velocity of unstretched flame and the Markstein length including thermal-expansion effects. When the flame radius was large, on the other hand, cellular surface induced by intrinsic instability was observed, and then the flame acceleration was confirmed. As the results, the critical flame radius corresponding to the occurrence of flame acceleration and the increment coefficient of propagation velocity were obtained. It was found that the increment coefficient became larger at low equivalence ratios, which was because the diffusive-thermal instability became stronger. Under the conditions of high concentration of inert gas, the increment coefficient of propagation velocity became smaller. This was because the burning velocity became lower by increasing the inert-gas concentration. Moreover, we obtained the increment coefficient normalized by the propagation velocity of unstretched flame. The normalized increment coefficient increased as the inert-gas concentration became higher, which indicated that the addition of inert gas promoted the instability of hydrogen flames. Based on the dynamic behavior and propagation characteristics of premixed flames, the parameters of flame acceleration model depending on the inert-gas concentration were obtained, and then the flame propagation velocity was predicted. 34.

Characteristics of spherically expanding hydrogen-methane-air lean premixed flames in a closed chamber: aiming to elucidate the hydrogen explosion at Fukushima Daiichi Nuclear Power Station

In the hydrogen explosion at Fukushima Daiichi Nuclear Power Station, the presence of flammable organic compounds together with hydrogen in reactor buildings was suggested. Aiming to elucidate the explosion characteristics, we performed the experiments of spherically expanding hydrogen-methane-air lean premixed flames in a closed chamber, where methane was adopted as a representative of flammable organic compounds. At sufficiently small flame radii, smooth flame surface was observed. The addition of methane to hydrogen-air mixtures generated the increase in the propagation velocity of unstretched flame. At large flame radii, cellular surface induced by intrinsic instability was found, and the flame acceleration was confirmed. The parameters of flame acceleration model were estimated, and then the flame propagation velocity depending on the flame radius was predicted. The normalized increment coefficient became larger at low equivalence ratios, owing to stronger diffusive-thermal instability. Under the same hydrogen concentration, the methane addition generated the increase in the maximum pressure in a closed chamber. The maximum pressure of experiments was lower than that of calculations, which was because of heat loss during premixed combustion. Under the same methane concentration, the pressure ratio of experiments and calculations was lower when the flame propagation velocity was smaller. This was because of larger heat loss. The obtained results were valuable information to elucidate the hydrogen explosion at Fukushima Daiichi Nuclear Power Station.

本事業では、1F1号機及び3号機の原子炉建屋において発生した爆発現象に関して、水素濃 度等及び可燃性有機ガスの影響を把握することを目的に、水素及び可燃性有機ガス濃度、初期 ガス温度をパラメータとして、火炎色等確認試験(拡散燃焼試験)及び予混合燃焼試験を計画し 実施した。そして、以下の結果と知見を得た。

(拡散燃焼)

・燃料にメタンが含まれている場合、薄オレンジ色の輝炎が観察されると共に、バーナー出口近傍 では青色の炎が観察される。前者は遊離した炭素から発せられるものであり、後者は CH 発光に よるものである。

・燃料が水素のみの場合、薄い赤い炎が観察される。これは暗室における試験において確認され るものであり、屋外では水素火炎を目視で確認することは困難である。

・ガス総流量が大きくなると、最高温度は若干上昇する。また、水素濃度が高い方が、最高温度は高くなる。これは、水素火炎温度の方がメタン火炎温度より高いからである。

・燃料に窒素を添加すると、火炎の色は薄くなり、火炎温度は低下する。

(予混合燃焼)

・火炎半径の増加と共に火炎面にセルが形成され、それが発達して複雑な形状になる。セルの形成は、火炎の固有不安定性によるものである。このセルの形成は従来の燃焼実験[5,9,10]でも観察され、JAEAの研究グループの数値計算[11]においても確認されている。

水素濃度が高くなると共に、火炎の伝播速度は増大する。これは予混合火炎の燃焼速度が大きくなるからである。また、容器内の最大圧力は上昇する。これは混合気の発熱量が大きくなり、火炎温度が高くなるからである。

・メタン濃度が高くなると共に、火炎の伝播速度は増大し、容器内の最大圧力は上昇する。前者は 予混合火炎の燃焼速度が大きくなることによるもので、後者は火炎温度が高くなることによるもの である。

初期温度が高くなると、火炎の伝播速度は増大する。これは予混合火炎の燃焼速度が大きくなるからである。

・容器内の最大圧力は、水素濃度及びメタン濃度が高くなる(つまり当量比が大きくなる)と共に、 ほぼ単調に上昇する。これは混合気の発熱量が大きくなり、火炎温度が高くなるからである。最 大圧力の上昇は、水素爆発による破壊力の強化に結び付くことから、1Fの水素爆発における可 燃性有機ガスの影響を精査することは非常に重要である。

・容器内圧力変化(時間履歴)の結果を、中間取りまとめ[1]に示されている解析結果と比較し、3 号機3階天井部の梁の損傷に関して、両者に整合性が有ることを確認した。

・本事業で得られた成果の一部は、英文学術雑誌に掲載されている[12]。

(今後の展望)

・海外の関連する組織との交流が必要である。フランスの関連組織 ICARE/CNRS は、本事業にも 関係するガス爆発の分野において、水蒸気を含めたガスを扱える密閉型容器を用いて実験を遂 行しており、世界でもガス爆発特性に関する知見を有する数少ない研究機関の一つである。この 研究機関と水素爆発に係わる情報を交換すると共に、共同での水素爆発試験の実施等を検討す ることが有用である。

・水素-メタン-空気予混合気の燃焼を取り扱っているが、不活性ガスとしての水蒸気や窒素の添加の影響を調べることが必要である。不活性ガス添加に係る知見は、1Fの水素爆発のメカニズムを把握し防爆対策を施す上で、非常に重要な情報となる。

本事業では、実験室レベルでの水素爆発の基本的な現象を観察している。実機等における爆発
現象を把握することは、次のステップとなる。その際、スケールの効果を考慮することが肝要である。

上記に加えて、水素及び混合気体燃焼に関する最新知見を収集し、拡散燃焼及び予混合燃焼 に関する知見を整理した。これらの知見は、1F事故における水素爆発のメカニズムを考察する上 で、また水素爆発における可燃性有機ガスの影響を精査する上で、有用な情報になるものであ る。

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本報告書に関する問い合わせは、原子力規制庁までお願いします。

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