

Review on fundamental combustion parameters of cryogenic fuel systems: Measurement techniques and experimental challenges

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ARTICLE INFO

Keywords:

Cryogenic fuel systems
Laminar burning velocity (LBV)
Minimum ignition energy (MIE)
Low-temperature combustion
Explosion and fire hazards
Heat flux burner methodology

ABSTRACT

Cryogenic systems are gaining increasing industrial relevance as decarbonization strategies promote the use of low-carbon energy carriers with very low normal boiling points. Their storage and transportation therefore require cryogenic conditions, introducing distinct safety and material challenges. Extremely low temperatures significantly alter thermophysical properties and reduce mechanical integrity, increasing susceptibility to brittle fracture and accidental release. In addition to direct cryogenic injury hazards, accidental releases may lead to severe fire and explosion scenarios, including flash fires, jet fires, vapor cloud explosions, pool fires, and boiling liquid expanding vapor explosions. Existing consequence assessment correlations have largely been developed for conventional fuels at ambient conditions and may not be directly applicable under cryogenic regimes due to strong temperature-dependent variations in density, viscosity, diffusivity, and heat capacity. Within this context, the experimental determination of fundamental combustion parameters such as the laminar burning velocity (LBV), flammability limits, and the minimum ignition energy (MIE) becomes essential. The LBV represents an intrinsic measure of mixture reactivity and plays a key role in assessing flame stability, ignition sensitivity, and explosion severity. This work systematically reviews established LBV measurement techniques and evaluates their suitability for low-temperature operation. Particular emphasis is placed on thermal management strategies and methodological limitations under cryogenic boundary conditions. Among the investigated approaches, the heat flux burner concept appears especially promising. In addition, experimental systems for determining the MIE at reduced temperatures are analyzed. Overall, the study highlights the necessity of specifically adapted experimental methodologies to ensure reliable safety parameters for cryogenic fuel systems.

1. Introduction

Cryogenic systems have become increasingly significant at the industrial level as their applications expand across diverse fields. Among the others, the current trends in decarbonization have supported the introduction of low-carbon species, characterised by lower normal boiling temperatures, thus promoting the liquefaction at cryogenic temperatures to optimise storage and transportation systems (Olewski et al., 2013; Pio and Salzano, 2018). The conditions that enable these innovations also introduce unique challenges that necessitate rigorous considerations. As a way of example, the extreme temperatures inherent to cryogenic environments can compromise material integrity, alter thermodynamic behaviour, and amplify risks associated with mechanical failure, leakage, or accidental release (Li et al., 2022). More

specifically, mechanical properties such as ductility, toughness, and fracture resistance are significantly reduced, increasing susceptibility to brittle failure, with obvious implications on the frequency of accidental release (Qiu et al., 2021). In addition, the use of extremely low conditions leads to specific hazards (Nubli et al., 2024). Indeed, exposure to temperatures far below the freezing point of water can cause instantaneous frostbite, leading to cellular destruction and necrosis (Uygur et al., 2009). Unlike conventional thermal burns, cryogenic burns often manifest with delayed pain responses, which may obscure the severity of the injury and hinder timely intervention. The rapid freezing of skin and underlying tissue can result in permanent damage, including loss of sensation, scarring, or, in extreme cases, amputation. In addition to direct dermal injury, cryogenic vapours pose further risks to exposed areas such as the eyes and respiratory tract. Cold vapours can damage

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<https://doi.org/10.1016/j.psep.2026.109493>

Received 1 March 2026; Received in revised form 15 August 2026; Accepted 20 August 2026

Available online 29 August 2026

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the corneal surface, impairing vision, while inhalation of cryogenic gases may irritate or injure delicate respiratory tissues (Kiss, 2012). However, these scenarios typically involve a limited impact area, where only authorised and trained personnel wearing suitable personal protective equipment have access; thus, a negligible effect on the overall risk figure is commonly associated with this kind of injury (Carboni et al., 2022a; de Liso et al., 2023).

More likely, fire-related scenarios are significantly contributing to the determination of local risk. Considering the cryogenic temperature as the initial condition and the properties of the involved species and mixtures, flash fire, jet fire, vapour cloud explosion (VCE), pool fire, and boiling liquid expanding vapour explosion (BLEVE) can be expected (L. Wasewar and Kumar, 2010; Mocellin et al., 2023). Several correlations for evaluating the source terms, the time evolution of the formed pool/cloud, and consequence analysis have been developed and validated against experimental data from scenarios caused by an accidental release of traditional fuels only (L. Wasewar and Kumar, 2010). In this sense, it is worth mentioning that thermophysical parameters, including density, viscosity, and heat capacity, undergo marked variations, which influence the determination of the source term, fluid dynamics, and heat transfer mechanisms (Liu et al., 2025). Hence, the applicability of existing correlations needs specific corroborative analyses based on robust and comprehensive experimental datasets. Moreover, the volatility and expansion characteristics of cryogenic fluids upon vaporisation can complicate predictive modelling and require specific analyses (Hansen, 2020). For these reasons, pool formation represents a critical phenomenon that requires specific considerations once cryogenic conditions are involved, especially in the case of a continuous release. Similarly, the accurate assessment of the evaporation rate is essential to properly account for the flammability and flame characteristics of the resulting mixture in the vapour phase (Nawaz et al., 2019). Besides, cryogenic vapours are typically denser than ambient air, and they can accumulate near the ground, leading to oxygen-deficient atmospheres. Hence, either a thermal or chemical stratification can be expected, affecting the physical and chemical properties at the microscopic scale as well as ignition likelihood and flame intensity at the macroscopic scale (Carboni et al., 2022b). These altered conditions demand specialised analytical frameworks that account for temperature-dependent deviations from standard assumptions, ensuring that consequence analyses remain robust and reliable under cryogenic regimes.

Under these premises, the experimental determination of the laminar burning velocity (LBV), representing the rate at which a flame front propagates through a quiescent premixed fuel-air mixture under laminar flow conditions, offers several potential advantages. Indeed, this property is not only a measure of the intrinsic reactivity of the fuel but also a key determinant of flame stability, ignition sensitivity, and the potential severity of fire and explosion scenarios. Besides, LBV can be employed for the validation of detailed kinetic mechanisms, allowing for advanced numerical simulations of reactive scenarios, as well as to estimate the flammability limits. Hence, the production of a robust and comprehensive experimental dataset is paramount to guarantee safe and optimised processes (Pio et al., 2024, 2020).

Minimum ignition energy (MIE) is the minimum electrical energy that, when released in a defined manner, is sufficient to ignite the most easily ignitable composition of a fuel-oxidizer mixture under specified conditions. It characterizes the sensitivity of a mixture to spark ignition and is typically defined as the energy stored in a capacitor and discharged across a fixed electrode gap. For gases and vapors, both capacitive and inductive discharges may occur in practice, although MIE is generally referenced to capacitor-stored energy. In dust testing, standards require an almost purely capacitive discharge because electrostatic sparks are inherently capacitive and MIE values are sensitive to the discharge waveform. Dust clouds also present additional complexity due to transient dispersion and inhomogeneity. Dust MIE is commonly determined in small-scale dispersion tubes (e.g., Hartmann-type apparatus), whereas gaseous mixtures are tested in closed vessels with

defined electrode geometries, as described in standardized methods (e.g., American Society for Testing and Materials procedures for gases and dusts).

Measured MIE values depend on parameters such as concentration, particle size (for dusts), oxygen content, pressure, temperature, humidity, and electrode configuration. Experimentally, ignition probability is determined from repeated tests at varying spark energies, and the MIE is often defined as the energy corresponding to a 50% ignition probability of the most easily ignitable mixture composition. At reduced temperatures and pressures, MIE generally increases due to slower reaction kinetics and reduced radical formation. Low-temperature testing requires controlled thermal conditions to ensure stable mixture preparation and discharge characteristics.

For these reasons, the existing experimental apparatus and protocols currently available for MIE and LBV have been described in the following paragraphs, highlighting the possible advantages and limitations in their possible use at cryogenic conditions.

2. Overview of the experimental systems suitable for measuring the laminar burning velocity

To determine the characteristic size of the adiabatic laminar burning velocity, various experimental methods have been developed over time. These methods have been comprehensively analyzed, summarized, and evaluated by Egolfopoulos et al. (2014) and Konnov et al. (2018). The measurement methods can be divided into two global categories: stationary and non-stationary combustion systems, and further distinguished into vessel and burner methods (Sven et al., 2025). All measurement methods developed so far can be categorized into these four groups, as shown in Fig. 1. Furthermore, in Fig. 2 the maximum possible temperature and pressure ranges of these methods were extracted from the literature. Some of the known methods are briefly explained below:

2.1. Conical flame / bunsen burner method

2.1.1. Concept of the conical flame / bunsen burner method

This method, one of the oldest for studying adiabatic laminar burning velocity, was first introduced in 1867 (Bunsen, 1867). It analyzes the angle between the flame fronts formed by a premixed conical flame at the exit of a burner. The setup produces a rotationally symmetric flame, which can be visualized using schlieren photography, chemiluminescence, or laser-induced fluorescence (LIF) (Meier et al., 2000). By detecting radicals like CH or OH, the flame front position is determined. The adiabatic laminar burning velocity (S_L) is calculated from the enclosed angle (α), the known flow rate, and the inflow velocity (u_0). This rather simple technique has some limitations from the

	stationary	Non-stationary
burner	- Cone flame-Bunsen burner - Counterflow burner - annual step wise tube - diverging channel - Heat Flux burner	- Flame pipes - annual step wise tube
vessel	Not known	- spherical combustion chamber „shock-tube“ - ST-burner - OPTIPRIME

Fig. 1. Classification of methods for determining the laminar burning velocity of known measuring methods for determining the LBV. 1 heat flux burner; 2 counterflow burner; 3 constant volume chamber; 4 constant pressure chamber; 5 OPTIPRIME; 6 conical flame/ Bunsen burner; 7 annual step wise tube; 8 diverging channel; 9a shock tube; 9b theoretical shock tube.

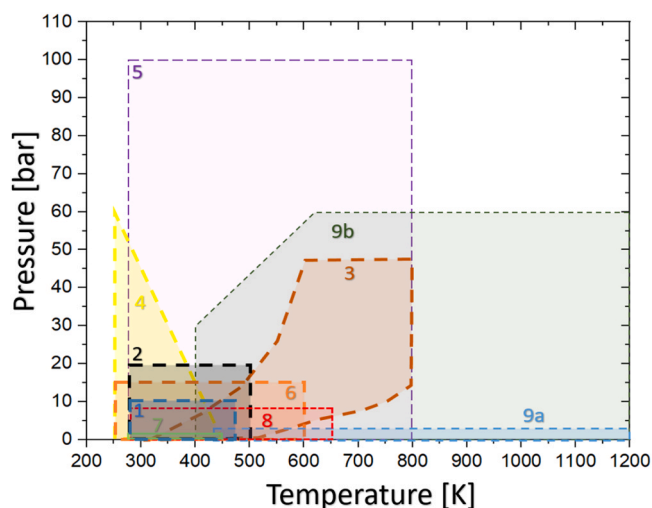


Fig. 2. Application limits of known measuring methods for determining the laminar burning velocity. 1 heat flux burner (Section 2.5); 2 counterflow burner (Section 2.3); 3 constant volume chamber (Section 2.2); 4 constant pressure chamber; 5 OPTIPRIME; 6 conical flame / Bunsen burner (Section 2.1); 7 annual step wise tube (Section 2.4); 8 diverging channel (Section 2.4); 9a shock tube; 9b theoretical shock tube. Figure adopted from (Eckart, 2022).

influence of flow near the burner mouth and flame curvature effects, which require corrections during the calculation of the LBV. Previous investigations (Scholte and Vaags, 1959) extensively used this method to analyze various fuel mixtures. Further advancements by Liu and MacFarlane (1983), Chung and Law (1988), and others improved accuracy by addressing flow and curvature effects, extending the method to turbulent flame speed measurements with different turbulence grids.

2.1.2. Cooling methodology of the conical flame / bunsen burner method

In the last decades, it has been shown that this technique could be adopted to various fuels and mixtures, and was also extended to turbulent flames. The feasibility for use in cold temperatures has been recently demonstrated by Ghosh et al. (2022a). However, controlled temperature regulation is not possible, especially for maintaining high volumetric flows over extended periods. Nonetheless, the introduction of the system into a cooled environment, such as an ultra freezer or a cryogenic cooler with liquid nitrogen, is conceivable for the gas mixing line. The curvature and elongation of the flame still cause uncertainties in the measurement methodology. The experimental study by Ghosh et al. (2022a) examined the influence of low temperatures on the laminar burning velocity and compared the experimental results with numerical simulations based on established chemical kinetic mechanisms. Specifically, perfectly premixed hydrogen–air, methane–air, ethane–air, ethylene–air, and propane–air flames were investigated at

near-cryogenic temperatures and atmospheric pressure, with measurements conducted down to approximately 160 K. Fig. 3 illustrates the experimental setup, which comprised a Bunsen burner equipped with liquid nitrogen cooling and an optical imaging system. The burner was designed to produce a top-hat velocity profile at the nozzle exit to ensure well-defined boundary conditions. Temperature control was achieved by submerging the burner in liquid nitrogen. Prior to entering the burner, the premixed fuel–air mixture was passed through a 90 cm long spiral copper tube that was likewise immersed in liquid nitrogen. The temperature of the mixture was regulated by adjusting the quantity of liquid nitrogen applied during the experiments.

They state that the data were acquired exclusively from stationary and stable flames. For each set of experimental conditions, flame stabilization was achieved by adjusting the bulk flow velocity until a steady, axisymmetric flame with a well-defined cone angle was established. This procedure ensured reproducible boundary conditions and minimized the influence of hydrodynamic instabilities or flame oscillations on the determination of the laminar burning velocity, nevertheless, the flames exhibited pronounced curvature effects next to the burner and at the flame tip. Fig. 4 illustrates a representative example of a stable, stoichiometric methane–air flame at an initial mixture temperature of 230 K. The methodology employed for the determination of the laminar burning velocity is based on the principle of mass conservation across the flame front. Under steady-state conditions, the mass flow rate must remain constant as the reactants pass through the flame and are converted into products. Accordingly, the mass flux entering the flame from the unburned side must equal the mass flux leaving it on the burned side. This relationship links the mass flow rate to the local density, the flame surface area, and the burning velocity on both sides of the flame front. For an idealized, one-dimensional, planar, and unstretched flame, the flame surface area does not change across the flame front. Compared to Ghosh et al. (2022a) (2022b), the present study of Michaux et al. (2025) offers several key improvements. First, the accessible temperature range is extended, reaching 100 K for H₂–air (vs. 150 K previously) and 150 K for CH₄–air (vs. 190 K previously). The most important methodological advance is the explicit control of thermal equilibration. Measurements are only taken once, when both the gas and nozzle thermocouples indicate the same temperature, a step requiring about 45 min at the lowest temperatures. This was not implemented in earlier work where only the nozzle temperature was monitored. For CH₄–air mixtures, also a different cooling approach was used. Instead of cold N₂ gas, liquid N₂ was added directly into an insulated cold box in small amounts, allowing lower temperatures to be reached without freezing the fuel. Finally, the present study (Michaux et al., 2025) achieves lower experimental uncertainty and better agreement with literature data at ambient temperature, reflecting an overall gain in measurement precision and reliability.

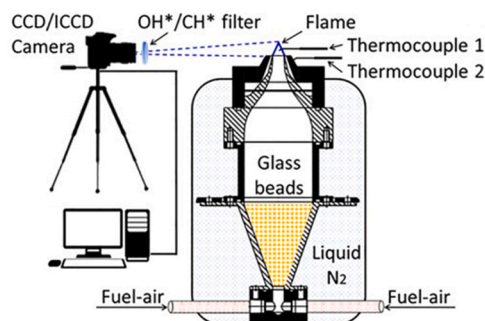


Fig. 3. Schematic of the experimental setup. Adapted from (Ghosh et al., 2022a).



Fig. 4. Example of methane–air flame at a temperature of 230 K, captured with a Digital Single-Lens Reflex camera. Adapted from (Ghosh et al., 2022a).

2.2. Spherical combustion chamber method

2.2.1. Concept of the combustion chamber method

The spherical combustion chamber method, see Fig. 5, involves igniting a premixed fuel-air mixture at the center of a closed chamber, allowing the flame front to propagate spherically. This process can occur under either constant pressure or constant volume conditions and is characterized by the flame's radius.

In flame propagation, the flame expands spherically within a closed chamber, and the flame front can be visualized using optical methods like schlieren photography and laser-induced fluorescence (LIF). This method has two main variants: the constant pressure method and the constant volume method. The constant pressure method analyzes combustion by maintaining a constant pressure throughout the process. Challenges in this method include accounting for ignition energy, radiation effects, and non-linear extrapolation. These factors require corrections to accurately determine the laminar burning velocity (LBV) (Clavin, 1985; Faghih and Chen, 2016). Over the past three decades, significant improvements and corrections have been summarized by researchers such as Egolfopoulos et al. (2014) (1991). The constant volume method, on the other hand, is evaluated through pressure-time relationships rather than optical methods. Early approaches were inaccurate because they neglected the effects of flame stretch. Recent approaches consider these effects, making it possible to estimate the unstretched LBV once the pressure exceeds 20% of its initial value. Despite these improvements, discrepancies in LBV data across different setups persist, complicating direct comparisons (Movaghar et al., 2020). In conclusion, the spherical flame method, both in its constant pressure and constant volume variants, provides essential insights into laminar burning velocities. However, careful corrections and considerations are necessary to address various influencing factors.

2.2.2. Cooling methodology of the combustion chamber method

In this method, active cooling is in principle feasible, either by implementing a double-walled chamber design with an integrated cooling circuit or by placing the entire combustion chamber within a temperature-controlled refrigeration environment. Both approaches allow the adjustment of the initial thermodynamic conditions and enable investigations at reduced ambient temperatures. However, each ignition event introduces a substantial thermal load into the chamber walls and optical components. The rapid release of chemical energy during combustion leads to a pronounced temperature increase of the surrounding materials, including the metallic enclosure and the glass windows used for optical diagnostics. Due to the comparatively high thermal mass of these components and the limited heat transfer coefficients typically achievable in such configurations, the subsequent cooling phase is inherently slow. As a consequence, very long waiting times between consecutive measurements are required to restore well-

defined and reproducible initial conditions.

Moreover, a reduction in the initial temperature has a direct influence on the fundamental combustion properties of the mixture. Lower temperatures decrease reaction rates and reduce molecular diffusivities, which in turn diminish the laminar burning velocity. This deceleration of the flame front can become significant, particularly in mixtures that already exhibit intrinsically low reactivity. Under such conditions, the flame propagation becomes increasingly susceptible to external perturbations. In particular, buoyancy effects may start to dominate the flame dynamics, as density gradients between burned and unburned gases induce convective motion. These buoyancy-driven distortions can alter the flame shape, stretch rate, and apparent propagation speed, thereby complicating the accurate determination of laminar burning velocities. Similar behavior has been reported for weakly reactive systems, such as ammonia-air flames, where slow laminar burning velocities enhance the influence of gravitational effects and lead to deviations from ideally spherical flame propagation (Kanoshima et al., 2022).

2.3. Counterflow burner

2.3.1. Concept of the counterflow burner

The stagnation or counterflow flame configuration, see Fig. 6, was proposed by Simmons and Wolfhard (1957) and is widely used to experimentally investigate the structure, stability, and extinction behavior of premixed and non-premixed flames. Law et al. developed the stagnation method to experimentally determine the extinction limits for propane-air mixtures. Law et al. (1981), along with Egolfopoulos and co-workers (Egolfopoulos et al., 1991), subsequently devised a method to extract laminar burning velocities from the counterflow configuration, assuming the centre as a 1-D laminar flame. The stagnation flow field is created either by influencing two identical jet streams or by directing a generated flow onto a wall. For a premixed fuel-air mixture, two identical flames are stabilized at equal distances from the stagnation plane, which eliminates downstream heat losses due to flame symmetry, with minimal radiation losses to the surroundings. The introduction of a nonlinear stretching correction led to reduced LBV values and smaller deviations in current methane comparison measurements. In contrast to methane, higher hydrocarbons exhibit greater uncertainties due to lower diffusion rates (Konnov et al., 2018). The impact of the Lewis number (Le , is a dimensionless number defined as the ratio of thermal diffusivity to mass diffusivity) on flame structure and LBV was investigated, revealing that flame behavior in hydrocarbon-rich mixtures is influenced by diffusion. The ratio of $S_{L,ref}$ to S_L remains independent of the Lewis number, with $S_{L,ref}$ increasing with flame stretching for $Le > 1$. For $Le < 1$ (Prieler et al., 2022; Han and Chen, 2015; Salusbury and Berghorson, 2015), as seen in hydrogen/air mixtures, reaction rates increase with stretching, affecting flame extinction behavior at shorter residence times. The uncertainties in the measurement method

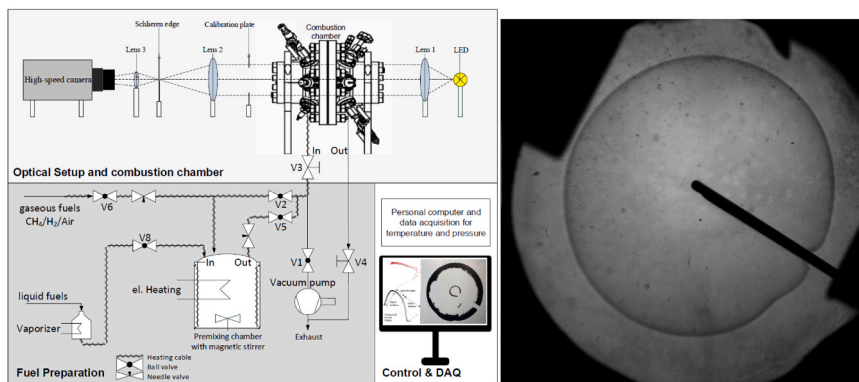


Fig. 5. Left: principle of the optical setup, the fuel preparation and control of the closed combustion vessel test rig at TUBAF and right: Flame front picture for 10% hydrogen admixture to methane at approximately 14 mm radius for equivalence ratio $\phi = 0,8$ for $P_u = 1$ bar (Eckart et al., 2022).

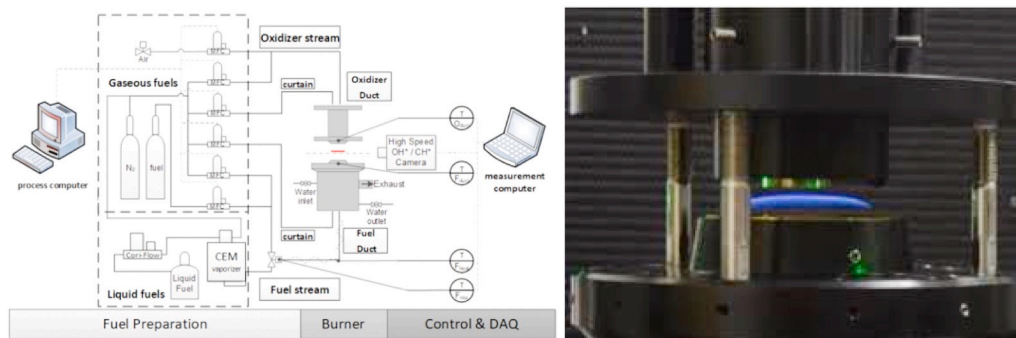


Fig. 6. Left: Schematic drawing of the experimental set-up with the counterflow burner (Eckart et al., 2023a) and right: stabilized methane flame (Eckart et al., 2021).

primarily arise from the control and management of flow measurement and mixture preparation.

2.3.2. Cooling methodology of the counterflow burner

In this method, not only the reactive jet streams but also the shilding flows, typically nitrogen or argon, must be cooled prior to entering the combustion region. Both the purge gas and the reactant jets remain within the burner body for a comparatively long residence time before discharge, which promotes thermal equilibration with the surrounding hardware. Consequently, the burner structure itself must be actively temperature-controlled to prevent unintended preheating of the incoming gases. Without sufficient thermal management, heat stored in the burner material from previous operation cycles may significantly alter the inlet temperature, thereby compromising the reproducibility of the boundary conditions. A chamber-based solution, in which the entire burner assembly is housed within a temperature-controlled enclosure, appears advantageous in principle. Such an arrangement would allow for global control of the ambient temperature and reduce uncontrolled heat exchange with the laboratory environment. However, in this specific configuration the flame is stabilized in open space between two opposing nozzles. The combustion products expand freely into the surroundings, and a substantial portion of the released thermal energy is transported away by the exhaust gases. This continuous heat release into the ambient environment leads to strong local temperature gradients and may interfere with attempts to maintain spatially uniform cooling conditions within the chamber. The resulting thermal stratification can introduce asymmetries in the flow field and modify the flame stabilization mechanism. Because the burner produces a stationary, time-independent flame, the system is particularly sensitive to even small variations in inlet temperature or local heat losses. Minor deviations can alter the density ratio, strain rate, and mixing characteristics at the stabilization plane, thereby affecting flame position and structure. For experiments conducted at reduced temperatures, these sensitivities become even more critical, as lower reactivity increases the susceptibility of the flame to perturbations. In its current configuration, the setup is therefore not readily adaptable to low-temperature operation. Effective implementation would require rapid and well-controlled cooling directly at the inlet section, analogous to the use of heating cartridges or preheating elements in high-temperature gas applications. Such an integrated cooling module would need to ensure precise temperature conditioning immediately upstream of the nozzles while minimizing axial temperature gradients and preventing condensation or compositional inhomogeneities. Without such modifications, reliable and stable operation under significantly reduced initial temperatures remains technically challenging.

2.4. Effects of wall interaction: annual stepwise tube method and the externally heated diverging channel

2.4.1. Concept of the annual stepwise tube method and the externally heated diverging channel

In both the annual stepwise tube method (Liu and Kim, 2014) and the externally heated diverging channel method (Kumar et al., 2020), a pronounced wall effect has been reported, as discussed in the review paper by Konnov et al. (2018). In these configurations, see Fig. 7, the flame front propagates in close proximity to the confining walls, which significantly influences flame structure, propagation speed, and extinction behavior. The interaction between the flame and the wall leads to enhanced heat transfer from the reaction zone to the surrounding material. As a result, the measured flame characteristics deviate from those of an ideal, freely propagating flame. This wall effect becomes even more critical under low-temperature conditions. At reduced initial temperatures, the flame is generally weaker and more sensitive to external disturbances. The larger quenching distance and the direct contact between the flame and the wall intensify conductive heat losses. These losses alter the local temperature field and can suppress or destabilize the flame, thereby affecting the determination of the limiting conditions. Consequently, additional corrections for heat losses would be required. However, these losses are difficult to quantify accurately because they depend on multiple factors, including wall material properties, surface temperature distribution, flow conditions, and flame-wall interaction dynamics. Without precise knowledge of these parameters, any correction would introduce further uncertainty into the measurement.

2.4.2. Cooling methodology of the annual stepwise tube method and the externally heated diverging channel

For these reasons, the application of the described methods in a low-temperature environment does not appear to be suitable for the exact determination of the LBV. The amplified wall effects, combined with increased heat losses and flame instability, would compromise measurement accuracy and reproducibility. Therefore, alternative experimental approaches or specifically adapted setups would be necessary to reliably measure the LBV under low-temperature conditions.

2.5. Heat flux burner

2.5.1. Concept of the heat flux burner

The Heat Flux burner method stabilizes a quasi-adiabatic flat flame and measures its laminar burning velocity (de Goey et al., 1993), see Fig. 8. This technique involves heating an unburned gas mixture from a heated burner plate, creating a quasi-adiabatic volume between the flame front and the plate. Radial temperature measurements are taken using thermocouples embedded in a highly perforated, conductive burner plate (Konnov et al., 2018). To maintain adiabatic conditions, a

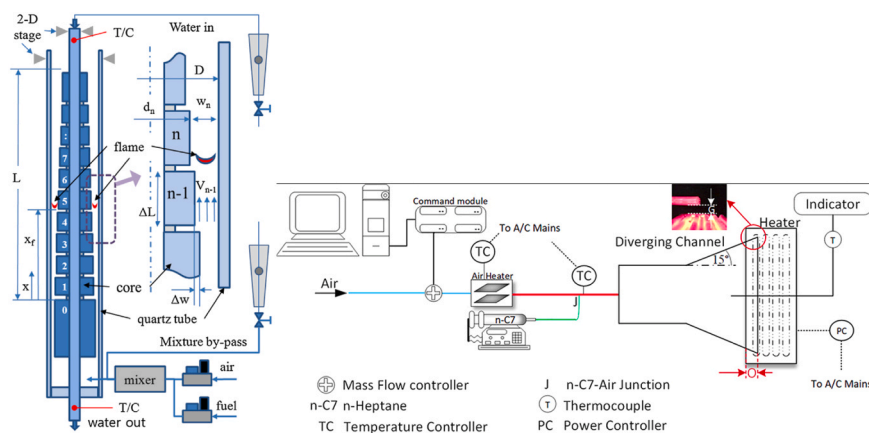


Fig. 7. Experimental apparatus of an annular stepwise diverging tube (Liu and Kim, 2014) and the externally heated quartz channel setup (Kumar et al., 2020).

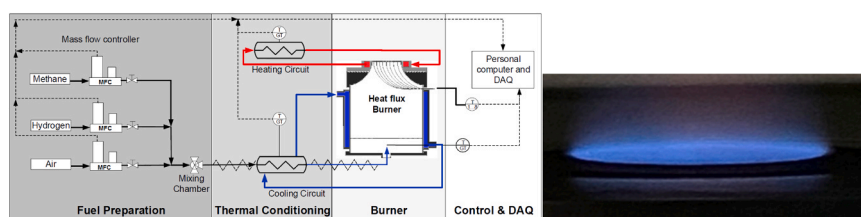


Fig. 8. Left: Heat flux burner test rig for gaseous fuels with fuel preparation and thermal oil cooling and heating system and right: flame formation of the heat flux burner flame at $T = 323\text{ K}$, $\Phi = 1$ (Eckart et al., 2023b, 2024).

heated jacket surrounds the plate, compensating for heat loss, while an additional heating circuit keeps the premixing chamber at the same temperature as the gas mixture. Extensive error analysis shows minimal variability in measurements, attributed primarily to mass flow controllers and thermocouples. The Heat Flux method produces reproducible results for both gaseous and liquid fuels and has been extended to high pressures (Goswami et al., 2016). These experimental studies have reported LBV measurements mixtures at pressures up to 10 bar, with an unburned gas mixture inflow velocity limited to $\sim 75\text{ cm/s}$. Research indicated (Wang et al., 2020) no significant interaction between the stabilized flame and the burner plate. Based on these insights, Han et al. (2021) developed a method to extrapolate burning velocities at specific feed gas temperatures, enabling measurements at temperatures up to 498 K, which could be also used for lower temperature in a certain range.

2.5.2. Cooling methodology of the heat-flux burner

This approach is regarded as one of the most technically feasible strategies for operation under cryogenic or sub-ambient temperature conditions, particularly in comparison with conventional Bunsen burner-based systems. Its feasibility arises from the relatively simple geometric configuration and the well-characterized thermal and fluid-dynamic behavior of flat-flame burners, which facilitate systematic thermal management modifications. For implementation at low temperatures, the entire inlet section of the burner assembly, including gas supply lines, mixing chamber, and upstream flow conditioning elements, would require active temperature control. This is essential to prevent premature condensation, density gradients, or viscosity changes in the reactant streams, all of which could significantly alter the Reynolds number and, consequently, the flow regime. Maintaining well-defined laminar flow conditions is critical, as the stability and structure of a flat flame are highly sensitive to perturbations in velocity profiles and mixture homogeneity.

In contrast to conventional configurations where a primary heating element stabilizes the reactant mixture, the modified system would

incorporate an actively cooled jacket surrounding the burner and mixing chamber. This cooling chamber would operate via a circulating cryogenic or refrigerated heat-transfer medium. The objective is to extract thermal energy uniformly from the premixed gases prior to combustion, thereby enabling well-defined initial temperature conditions without introducing strong spatial gradients. Additionally, the integration of an internal heat exchanger within the mixing chamber could further enhance thermal uniformity. By directing a controlled flow of a cold medium through embedded channels, the reactant mixture temperature can be precisely adjusted while preserving laminar flow characteristics. The heat exchanger design must ensure minimal disturbance to the velocity field; therefore, smooth channel geometries and low-pressure-drop configurations are essential to avoid transition to turbulence. Downstream, the secondary thermal control circuit associated with the burner plate would be regulated to maintain a temperature differential comparable to that of conventional flat-flame burners. This controlled temperature gradient is crucial for stabilizing the reaction zone and maintaining the quasi-adiabatic conditions characteristic of flat-flame operation. At the same time, the system must allow combustion products to be efficiently exhausted from the chamber to prevent back-pressure effects or recirculation phenomena that could compromise flame stability.

Overall, the proposed configuration preserves the fundamental operating principle of a quasi-adiabatic flat flame while extending its applicability to low-temperature boundary conditions. Due to the comprehensive thermal management strategy, encompassing inlet conditioning, controlled cooling, and stabilized burner plate temperature, it is anticipated that this system would provide superior reproducibility, well-defined boundary conditions, and consequently the highest attainable measurement accuracy among the considered approaches.

2.6. System boundaries and limitations for laminar burning velocity

The determination of laminar burning velocity at cryogenic temperatures faces several key experimental limitations. Maintaining a

uniform temperature field is difficult, and even small gradients can alter local gas density and reactivity, so the nominal temperature may not reflect actual conditions at the flame. Condensation of mixture components on cold surfaces can further shift the effective composition, challenging the assumption of a homogeneous premixture. Cold walls or burner hardware act as heat sinks, enhancing quenching and potentially lowering the measured LBV beyond what chemistry alone would predict, while reduced reactivity at low temperature increases sensitivity to buoyancy-driven distortions. Instrumentation must also remain reliable under cryogenic conditions, and sufficient thermal equilibration time is needed to ensure reported temperatures match actual gas conditions. Together, thermal non-uniformity, phase-change effects, enhanced heat losses, and diagnostic constraints define the principal limitations of cryogenic LBV measurements. (Table 1)

3. Overview of the experimental systems suitable for measuring the minimum ignition energy

Minimum ignition energy (MIE) is usually determined by igniting a well-defined fuel–air mixture with an energy-controlled source and then systematically reducing the energy until ignition is just no longer possible (Wöhner et al., 2013; Su et al., 2024; Randeberg and Eckhoff, 2007). Several experimental setups are used, most of them differing in geometry, ignition source, and whether the fuel is a gas, vapor, or dust (ASTM E2019–03, 2019). Three main experimental methods are commonly used for minimum ignition energy (MIE) measurement: (1) capacitive spark in standardized gas/vapor systems, (2) Hartmann tube (Janes et al., 2008) for dust clouds, and (3) 20 L sphere-type explosion vessels for dusts. Each method controls ignition energy and mixture conditions differently, but all determine MIE by bracketing the lowest energy that still leads to a self-sustained ignition (staubex.ifa, 2015).

3.1. Burner method: experiments / cooling methodology

3.1.1. Concept of the burner method

The minimum ignition energy (MIE) of hydrogen–air mixtures was determined at atmospheric pressure over a wide range of concentrations and temperatures, including cryogenic conditions down to

approximately $-140\text{ }^{\circ}\text{C}$ (Jordan et al., 2019). The experimental setup was designed to ensure precise control of mixture composition, temperature, and spark energy, while minimizing systematic uncertainties typical of conventional ignition systems. Hydrogen and synthetic air (20.9% O_2 in N_2 , low humidity) were supplied from gas cylinders and metered using calibrated mass flow controllers. The oxygen concentration was continuously monitored with a paramagnetic analyzer, and the hydrogen concentration was calculated accordingly, with an estimated uncertainty of $\pm 0.5\%$ v/v. Spatial homogeneity of the mixture at the burner exit was verified prior to testing. Ignition experiments were performed in a vertical cylindrical burner (inner diameter 40 mm, height 400 mm) filled with glass beads and thermally insulated. The mixture entered from the bottom and flowed upward through the porous bed. Ignition was initiated just above the bead surface. In case of ignition, flame propagation was confined above the bed, which acted as a flame arrestor and ensured safe operation. For cryogenic measurements, the bead bed was precooled by adding approximately 2 L of liquid nitrogen, allowing mixture temperatures down to $-120\text{ }^{\circ}\text{C}$ to $-140\text{ }^{\circ}\text{C}$ for a test duration of about 30 min. Ignition was generated by a specially developed two-stage spark system consisting of a high-voltage breakdown phase and a low-voltage arc phase. Tungsten electrodes (0.3 mm diameter) with a fixed 0.5 mm gap were used. The high-voltage circuit created the electrical breakdown, while a capacitor-based low-voltage circuit delivered the controlled ignition energy. Capacitances between 10 and 1000 pF and charging voltages of 400–1000 V were applied. Voltage and current at the spark gap were recorded, and the dissipated spark energy was determined by time integration of the product of both signals (Jordan et al., 2019), see Fig. 9. Approximately 50% of the stored capacitor energy was delivered to the spark gap under typical conditions. The MIE was determined using a descending-energy method. For each concentration and temperature, the spark energy was gradually reduced from a reliably igniting level until ignition no longer occurred. Repeated trials allowed identification of the ignition threshold with minimal overlap between ignition and non-ignition events. At ambient temperature, the minimum MIE occurred near 20% hydrogen and was approximately 18–20 μJ . At $-100\text{ }^{\circ}\text{C}$, the minimum remained at the same concentration but increased to about 50 μJ . A systematic temperature study at 20% hydrogen showed a monotonic, non-linear

Table 1

Comparison of low-temperature laminar burning velocity measurement methods.

Method (Section)	Measurement Principle	Detection / Evaluation	Achievable Low-Temperature Range	Cooling Feasibility	Main Limitations / Uncertainties
Conical Flame / Bunsen Burner	Flame angle of a premixed conical flame	Schlieren photography, chemiluminescence, LIF	100 K (H_2 –air) and 150 K (CH_4 –air) (Michaux et al.)	Conditionally feasible, LN ₂ cooling of the burner and gas-mixing line is possible, but precise temperature control is difficult to maintain at high volumetric flow rates	Flow effects near the burner mouth, flame curvature effects, correction procedures required
Spherical Combustion Chamber	Spherically propagating flame under constant-pressure or constant-volume conditions	Optical methods (schlieren, LIF) or pressure–time analysis	In principle feasible via double-walled/cooled chamber design	Generally feasible, but long equilibration times are required between measurements due to the high thermal mass of chamber walls and optical windows	Increasing influence of buoyancy-driven distortions at low reactivity, slow thermal recovery of the chamber
Counterflow Burner	Stagnation-flow configuration with two opposed, symmetric flames	1-D flame analysis, nonlinear stretch correction	Currently not practicable at low temperatures	Limited feasibility, open exhaust configuration produces strong local temperature gradients; active cooling of nozzles/burner body would be required	Heat exchange with burner hardware, poor reproducibility of inlet temperature
Wall-Interaction Methods: Annular Stepwise Tube / Externally Heated Diverging Channel	Flame propagation in close proximity to confining walls, quenching behavior		Not suitable	Not suitable, pronounced wall heat losses and flame instability are amplified at low temperatures	Quenching distance, wall heat losses difficult to quantify accurately
Heat Flux Burner	Quasi-adiabatic flat flame stabilized on a perforated plate	Radial thermocouple measurements	Demonstrated up to 498 K (Han et al.); extension to sub-ambient temperatures conceptually proposed	Most promising approach, actively cooled jacket, conditioned inlet section, stable laminar flow conditions achievable	Requires precise thermal management to avoid condensation, density gradients, or viscosity-induced flow instabilities

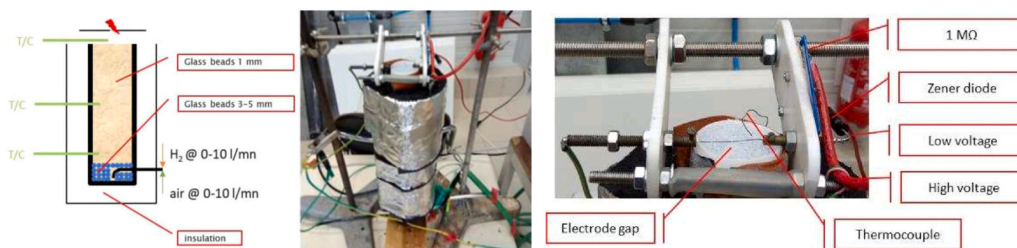


Fig. 9. Left and middle: burner setup (40 mm ID and 400 mm high), right: spark gap arrangement and from project PRESLEY (Cirrone et al., 2023).

increase in MIE with decreasing temperature.

As described previously for laminar burning velocity measurements, Ghosh et al. employed a conical flame/Bunsen burner method (Ghosh et al., 2022b), see Fig. 10. This experimental configuration was subsequently extended for the measurement of the minimum ignition energy of premixed methane–air and hydrogen–air mixtures at temperatures as low as 200 K. The adapted setup combined a nitrogen-cooled Bunsen burner with a controlled spark ignition system, enabling precise control of mixture temperature, composition, and deposited spark energy. The ignition system consisted of a pulse/delay generator, a high-voltage amplifier, a 1 kΩ resistor, and two copper pin electrodes. The electrodes had a diameter of 100 μm and were separated by a 1 mm gap. The center of the electrode gap was positioned along the burner symmetry axis, 2 mm above the nozzle exit. The spark duration was fixed at 100 μs. Voltage and current signals were measured using a high-voltage probe and a current monitor and recorded with an oscilloscope. The deposited spark energy was determined by integrating the product of voltage and current over the entire discharge duration. The system allowed variation of the spark energy between 0.1 mJ and 1.6 mJ, with an estimated uncertainty of ±10%. Due to the short spark duration, heat losses to the electrodes and the surrounding flow were considered negligible. Ignition detection depended on the fuel. Methane flames were identified by direct visual observation. In contrast, hydrogen flames, which emit predominantly in the ultraviolet spectral range, both were also detected using a T-type thermocouple positioned 15 mm above the electrodes along the burner axis. Successful ignition was indicated by a measurable temperature increase at this location. For each operating condition, multiple spark events were conducted to determine whether ignition occurred.

3.2. 20 L sphere (Siwek Chamber) / cooling methodology

3.2.1. Concept of the 20 L sphere

The 20 L sphere (El-Zahlanieh et al., 2025; Heilmann et al., 2024; Spitzer et al., 2022), commonly referred to as the Siwek chamber, is a standardized spherical explosion vessel used to characterize the ignitability and explosion severity of combustible dusts, gases, and mists (Portarapillo et al., 2025). It is widely applied to determine parameters such as the maximum explosion pressure, the maximum rate of pressure

rise and the minimum explosive concentration in accordance with established standards. With suitable modifications, the same apparatus can also be employed to determine the minimum ignition energy (Heilmann et al., 2024). The system consists of a 20 L stainless-steel spherical vessel (partly equipped with ports for material dispersion, see Fig. 11), a centrally located ignition source, high-speed pressure transducers, and connections for vacuum evacuation and compressed air supply. Prior to testing, the vessel is evacuated to a defined sub-atmospheric pressure. A precisely weighed number of combustible gases, liquids or materials is then dispersed into the chamber. After a defined ignition delay, the ignition source is activated and the pressure-time history is recorded. For explosion testing, high-energy pyrotechnic igniters, sparks or hot wires are used to ensure reliable ignition across a broad range. In contrast, MIE determination requires calibrated low-energy ignition systems, such as capacitive spark devices, allowing systematic variation and quantification of ignition energy. The ignition energy is progressively reduced at a near-optimal concentration until ignition just fails. The MIE is defined as the lowest energy that still produces a characteristic rapid pressure rise exceeding a specified overpressure criterion. Because the igniters themselves generate a measurable pressure rise, reference tests without combustibles are performed to quantify and subtract this contribution. This correction is essential to avoid underestimating the true MIE. The instrumentation enables clear discrimination between non-ignition, weak combustion,

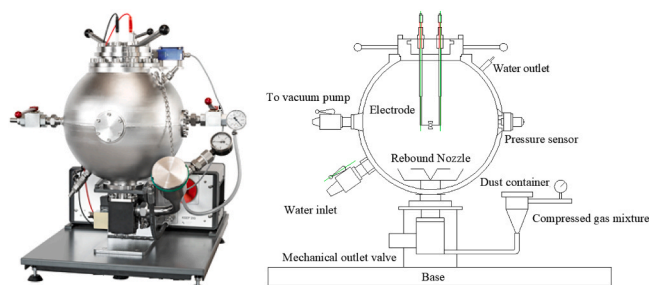


Fig. 11. Schematic diagram of the 20-L explosion sphere (Cesana-AG, 2026; Zhao et al., 2020).

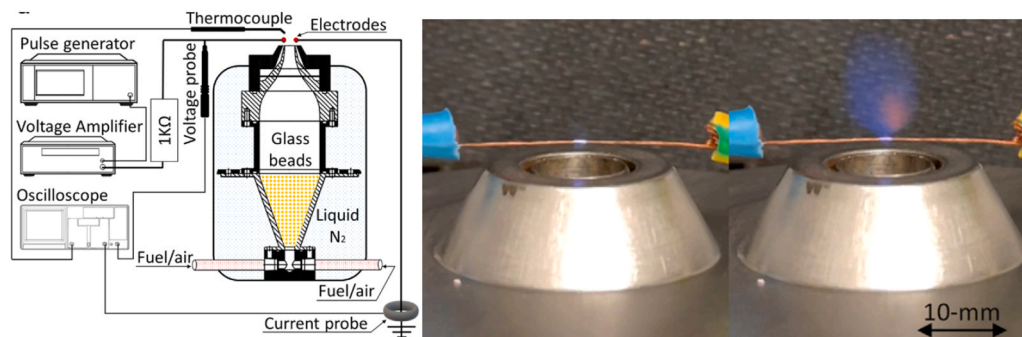


Fig. 10. Schematic of the experimental setup used, and direct visualization of a spark event without ignition, and a spark event with ignition (Ghosh et al., 2022b).

and fully developed explosions. Compared to smaller-scale devices, the 20 L sphere provides a larger volume, improving the relevance of the results for industrial applications. However, local concentration inhomogeneities near the ignition source may introduce uncertainty, particularly for highly sensitive combustibles. Despite these limitations, the 20 L sphere remains a robust and standardized tool for investigating ignition sensitivity.

3.2.2. Cooling methodology of the 20 L sphere

Cryogenic 20 L explosion chambers are modified versions of the standard 20 L spherical gas explosion vessel, designed to investigate the influence of low initial temperatures on gas explosion behavior. The basic geometry remains unchanged to ensure comparability with ambient tests. The key modifications concern thermal control and material compatibility. External cooling systems, such as refrigerant jackets or cooling coils, are installed to reduce the vessel and gas mixture to temperatures as low as approximately $-60\text{ }^{\circ}\text{C}$ (OZM Research s.r.o., 2025), see Fig. 12. Critical components, including seals, flanges, sight glasses, and electrical feedthroughs, must be made from low-temperature-resistant materials to prevent embrittlement and leakage during thermal cycling. Accurate temperature control is achieved using additional sensors (e.g., thermocouples or RTDs) placed in the gas phase and at the vessel wall to monitor thermal gradients. Cooling is performed stepwise with stabilization periods before ignition to ensure well-defined initial conditions. The experimental procedure follows the standard sequence, evacuation. Nevertheless, scientific sources using this setup are sparse or not existing.

3.3. Explosion vessel by Cui et al

3.3.1. Concept of the explosion vessel by Cui

The experiments of Cui et al. (2016)a were conducted in a stainless-steel explosion vessel to investigate ignition behavior over a broad range of thermodynamic conditions, see Fig. 13. Depending on the objective, the initial temperature ranged from 123 to 273 K (low-temperature operation using a cooling system (Cui et al., 2016a)) or from 30 to 150 $^{\circ}\text{C}$ (temperature-controlled heating chamber (Cui et al., 2016b)), while the initial pressure varied between 0.1 and 0.9 MPa. In the low-temperature configuration, the vessel had a height of 300 mm, an inner diameter of 100 mm, and a wall thickness of 25 mm, corresponding to a calculated pressure resistance of 45 MPa. For elevated



Fig. 12. Explosion chamber for gases, vapors, and dusts, approx. 20 L (CRYO version) (OZM Research s.r.o., 2025).

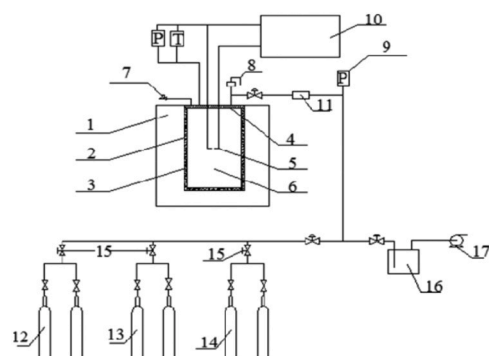


Fig. 13. Schematic diagram of the chamber (Cui et al., 2016a): 1-Cooling box, 2-Inner wall of the cooling box, 3-Aluminium powder, 4-Insulating layer, 5-Ignition electrode, 6-Explosion vessel, 7-Sampling valve, 8-Safety valve, 9-Precision pressure gauge, 10-Data acquisition system, 11-Flame arrester, 12-Methane gas cylinders, 13-Oxygen gas cylinders, 14-Nitrogen gas cylinders, 15-Needle valve, 16-Vacuum vessel, 17-Vacuum pump (Cui et al., 2016a).

temperatures, a vessel with a height of 400 mm, an inner diameter of 140 mm, and a wall thickness of 18 mm was used, rated for 15 MPa. The vessel was installed either in a cooling chamber (down to 123 K) or in a temperature-controlled heating chamber (up to 150 $^{\circ}\text{C}$). The initial gas temperature was measured near the vessel center using a fast-response thermocouple (accuracy $\pm 2\text{ }^{\circ}\text{C}$ or $\pm 2.7\text{ K}$), and the initial pressure was recorded with a precision pressure gauge (uncertainty $\pm 0.32\text{ kPa}$). Explosion pressures were measured by a piezoelectric pressure transducer with microsecond response time. Pressure and temperature data were acquired at a sampling rate of 500 kHz. An ignition event was defined as a pressure rise exceeding 5% of the initial pressure, in accordance with BS EN 1839:2003. Gas mixtures of methane, oxygen, and nitrogen were prepared using the partial pressure method. After evacuating the vessel, methane was introduced to the desired partial pressure, followed by nitrogen and oxygen. Ignition was achieved using a capacitor discharge system with capacitances starting from 4 pF and charging voltages between 1000 and 9000 V, corresponding to a minimum stored energy of approximately 0.002 mJ. Two stainless-steel needle electrodes (1 mm diameter, 60 $^{\circ}$ tip angle, 1 mm gap) were mounted at the vessel center. The actual spark energy was determined from simultaneous voltage and current measurements, thereby accounting for circuit resistance and stray capacitance. The combined uncertainty of the ignition energy determination was approximately $\pm 2\%$. For MIE determination, the capacitance was gradually reduced after successful ignition, followed by stepwise reduction of the charging voltage. The minimum energy at which no ignition occurred in 25 consecutive trials was defined as the MIE. A waiting period of 15–20 s between discharges ensured dissipation of residual energy. Each operating condition was tested in triplicate to ensure reproducibility.

3.3.2. Cooling methodology of the explosion vessel by Cui

Measurements under low-temperature conditions could successfully be conducted using the present experimental setup. However, these measurements represent the only experiments performed under such conditions with this configuration. To the best of our knowledge, no real-image documentation of the setup operating under these specific low-temperature conditions is available. The main challenges encountered in this study arise from the thermodynamic behavior of the combustible gas mixture under low-temperature and high-pressure conditions. The combustible gas consists of methane, nitrogen, and oxygen. At very low initial temperatures, down to 123 K, the gas mixture no longer behaves as an ideal gas. Under such conditions, the ideal gas equation of state is not applicable, and concentrations calculated using the partial pressure method deviate significantly from the actual values. To ensure accurate determination of the combustible gas composition, a

gas sample is extracted from the vessel prior to ignition and analyzed using gas chromatography (GC). The concentration measured by GC is then regarded as the true initial concentration. However, when the initial temperature is sufficiently low and the initial pressure is high, for example, at 143 K and 0.9 MPa, methane may liquefy, resulting in the presence of a liquid phase inside the explosion vessel. Under such conditions, the gas composition changes with variations in temperature and pressure, making accurate concentration measurements more difficult. Furthermore, substantial evaporation of the liquid phase may pose safety risks to the experimental setup due to rapid pressure fluctuations. Consequently, experimental conditions involving combinations of high pressure and very low temperature must be avoided to ensure both measurement accuracy and operational safety.

3.4. 7 l transparent cylindrical chamber: setup and experiments / cooling methodology

3.4.1. Concept of the 7 l transparent cylindrical chamber

In the study from Jordan et al. (2019), the experimental setup for determining the Minimum Ignition Energy is based on a transparent cylindrical explosion chamber with a volume of 7 L, rated for static pressures up to 100 bar. The transparent design enables optical diagnostics of flame kernel development using high-speed imaging (up to 10,000 fps), while ignition events are additionally identified through pressure measurements obtained from a piezoresistive transducer. The combustible mixture is prepared externally in a 0.1 L stainless-steel mixing vessel equipped with mass flow controllers to ensure accurate dosing of the individual gas components. Mixture composition is verified using a paramagnetic oxygen analyzer installed both upstream and downstream of the explosion chamber. This arrangement allows precise adjustment of the fuel–air ratio (e.g., 5 vol% $\pm$ 0.1 vol%), which is critical given the strong sensitivity of MIE to mixture composition (Jordan et al., 2019). Ignition is generated by two centrally positioned tungsten electrodes with a diameter of 0.3 mm. The use of tungsten reduces electrode erosion and associated energy losses. To minimize conductive heat losses and quenching effects, the electrode supports are placed several centimeters away from the spark gap. The electrode spacing can be adjusted depending on the mixture under investigation. A key innovation highlighted in the study is the implementation of a two-stage spark generation system. The first stage employs a high-voltage, high-impedance circuit (up to approximately 6 kV) to produce a low-current streamer discharge, which ionizes the gas and establishes a conductive path between the electrodes. In the second stage, a separate low-voltage, low-impedance circuit delivers the main ignition energy in the form of an arc discharge. The ignition energy is stored in a 20 nF capacitor charged up to 400 V, corresponding to an adjustable energy range of approximately 10–2000 μ J. Zener diodes electrically isolate the two circuits, while an optional series inductance (up to 1 mH) limits the discharge current and prolongs the spark duration, thereby improving energy transfer efficiency and reproducibility. During each discharge, both current and capacitor voltage are monitored, enabling estimation of the effective energy delivered to the spark gap. For MIE determination, the charging voltage is progressively reduced and multiple ignition trials are conducted at each energy level. Ignition is confirmed through pressure rise and optical observation of flame development. The MIE is defined as the lowest energy at which reproducible ignition of the mixture is observed.

3.4.2. Cooling methodology of the 7 l transparent cylindrical chamber

To adapt the described MIE setup for operation at cryogenic temperatures, the explosion chamber must be equipped with an appropriate cooling system, such as a cryogenic jacket supplied with liquid nitrogen or a cryocooler-based cold plate, see Fig. 14. Thermal insulation or vacuum jacketing may be required to minimize heat influx and ensure temperature stability but reducing the optical possibility. Multiple temperature sensors distributed within the chamber, particularly near

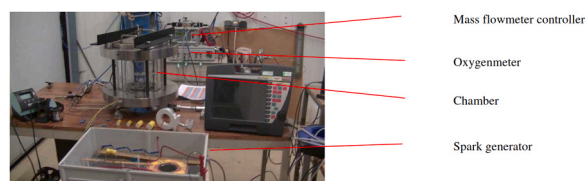


Fig. 14. Experimental setup of the 7 l transparent cylindrical chamber from Proust (Proust, 2021).

the spark gap, are necessary to guarantee temperature homogeneity. Metallic sealing systems should replace conventional elastomer seals to maintain leak tightness at low temperatures. The ignition electrodes can remain inside the cooled chamber, while sensitive electronic components, such as high-voltage generation and energy storage elements, should preferably remain outside and be connected via hermetic cryogenic feedthroughs. The two-stage spark concept remains advantageous, as it allows controlled discharge behavior even under altered breakdown conditions at low temperature. A gas precooling stage upstream of the chamber can be implemented using a controlled heat exchanger, ensuring that the mixture enters the chamber close to the target temperature. Care must be taken to prevent condensation of mixture components, as phase changes would alter composition and compromise reproducibility. Moisture must be rigorously eliminated through purging and gas drying to avoid frost formation on electrodes and optical windows. Integration of the ignition system within a larger vessel, such as a 20 L chamber, could be feasible.

3.5. System boundaries and limitations for MIE

The determination of Minimum Ignition Energy at cryogenic temperatures is subject to significant experimental constraints that affect accuracy and reproducibility, see Table 2. Unlike measurements at ambient conditions, cryogenic experiments involve complex thermal, physical, and metrological challenges that must be carefully considered when interpreting results. A primary limitation is thermal management, establishing and maintaining a uniform temperature field within the vessel is difficult, and even small gradients cause local variations in gas density and flammability, since perfect isothermality is practically unattainable and the nominal temperature may not represent the actual conditions at the ignition site. Closely related is the accuracy of the temperature measurement itself, which remains a frequently underestimated source of systematic uncertainty. Thermocouples, the standard sensor in both LBV and MIE setups, are prone to radiative heat exchange with surrounding surfaces at different temperatures (e.g., cold walls, flame fronts, cryogenic jackets), which can cause significant deviation from the true gas temperature unless explicitly corrected, introducing a systematic bias that risks being misattributed to deficiencies in chemical mechanisms rather than to measurement error. Further sources include finite sensor response time, conductive losses along the leads, and calibration drift under cryogenic cycling, so given the limited number of dedicated low-temperature setups, future studies should explicitly report their temperature correction methodology to enable meaningful comparison across datasets. A further challenge concerns mixture homogeneity and phase transitions. At cryogenic temperatures, components such as oxygen and nitrogen may condense on cold surfaces, altering the composition of the remaining gas phase, and local oxygen enrichment or depletion near the electrodes can significantly affect ignition behavior, so the assumption of a homogeneous mixture is not always valid under these conditions. The ignition process itself is strongly affected by the cryogenic environment, as flame kernel formation requires that chemical heat release exceed heat losses to the surroundings, cold electrodes act as heat sinks, enhancing quenching and potentially suppressing ignition, so the measured MIE may be artificially elevated, reflecting additional energy needed to

Table 2

Comparison of low-temperature minimum ignition energy (MIE) measurement methods.

Method (Section)	Measurement Principle	Detection / Evaluation	Achievable Low-Temperature Range	Cooling Feasibility	Main Limitations / Uncertainties
Burner Method	Capacitive two-stage spark ignition above a porous glass-bead bed / conical Bunsen-type flame	Voltage–current integration for spark energy; visual/UV detection or thermocouple for ignition confirmation	Down to ~133 K, demonstrated	Demonstrated feasible, LN2 precooling of bead bed or burner body; stable for ~30 min test duration	Non-linear MIE increase at low temperature, limited hold time before re-warming, electrode heat losses
20 L Sphere / Siwek Chamber	Central low-energy capacitive spark ignition in a dispersed gas/dust mixture within a spherical vessel	Pressure–time history via high-speed transducers; overpressure criterion for ignition	Down to ~213 K in cryogenic CRYO version	Feasible via refrigerant jacket/cooling coils; requires low-temperature-resistant seals, flanges, and feedthroughs	Local concentration inhomogeneities near ignition source; very limited/sparse literature data at cryogenic conditions
Explosion Vessel by Cui	Capacitor discharge ignition via needle electrodes in a stainless-steel high-pressure vessel	Piezoelectric pressure transducer; ignition defined by 5% pressure rise (BS EN 1839:2003)	Down to 123 K, demonstrated, at pressures up to 0.9 MPa	Demonstrated feasible, external cooling chamber; only a single known study at these conditions	Non-ideal gas behavior at low T/high p, possible methane liquefaction below ~143 K, safety risk from rapid evaporation
7 L Transparent Cylindrical Chamber	Two-stage capacitive spark ignition with optical flame-kernel imaging in a pressure-rated transparent vessel	High-speed imaging (up to 10,000 fps) combined with piezoresistive pressure measurement	Not yet demonstrated; cryogenic adaptation conceptually proposed	Conceptually feasible, cryogenic jacket/cold plate, metallic seals, hermetic feedthroughs for electronics; optical access trade-off with insulation	Risk of condensation/frost on electrodes and optical windows, reduced optical access if insulated, homogeneity near spark gap

overcome thermal losses rather than chemistry alone, while differences in electrode geometry and material further contribute to variability between studies.

The flow regime at ignition is likewise critical for interpreting MIE data. Chamber methods, such as the 20 L sphere, assume a nominally quiescent mixture, though residual turbulence from filling is hard to verify and its effect on MIE remains unclear. Burner methods supply the mixture under inflow conditions kept laminar by burner design, including flow straighteners, porous beds, and nozzle geometry, however, decreasing temperature alters gas density, viscosity, and flow rate, and thus the local Reynolds number, so laminar conditions must be verified for each case rather than assumed. This is particularly relevant for discharges from ruptured or depressurizing vessels, which are typically highly turbulent, and extrapolating laminar or quiescent MIE data to such scenarios therefore requires caution, since turbulence significantly affects ignition probability and effective ignition energy. Finally, instrumentation and diagnostic uncertainties add to the overall limitation, sensors must be suitable for cryogenic operation, and the effective spark energy delivered is always lower than the nominal stored electrical energy, with variations in discharge efficiency introducing additional uncertainty into reported MIE values.

4. Conclusions and outlook

This review assessed established experimental methods for determining laminar burning velocity (LBV) and minimum ignition energy (MIE), with emphasis on their applicability at reduced and cryogenic temperatures. The development of robust and rigorous methods suitable for the production of a reliable dataset of LBV and MIE at targeted conditions is particularly relevant for the process safety from different perspectives: (i) being the laminar burning velocity a parameter directly employed for the assessment of the severity of accidental releases of flammable vapour in the atmosphere; (ii) supporting the identification of flammable regions in terms of composition (e.g., lower flammability limits, upper flammability limits, and minimum oxygen concentration), temperature (e.g., flash point), and required energy by the combination of LBV and MIE data; (iii) guiding a proper design of containing and mitigation systems; (iv) allowing for a data-driven production and validation of advanced models, either fluid dynamics kinetics.

In view of the highlighted points, it should be noted that advanced cryogenic models are highly relevant to process safety because fluids at extremely low temperatures behave in ways that conventional correlations and empirical tools cannot capture, and overlooking these effects can lead to serious underestimation of hazards. As a way of example,

estimating the pressure dynamics, boil-off generation, stratification, rollover, and rapid phase transition requires specialized models to properly size the storage and relief systems. Therefore, integrating cryogenic-aware computational fluid dynamics (CFD), kinetic modeling, and structural analysis has become a cornerstone of modern process safety for several industrial applications, including hydrogen technologies, LNG infrastructure, and aerospace propellant systems.

Generally, CFD at cryogenic temperatures is challenging because fluid behaviour near boiling or critical conditions departs sharply from the assumptions built into standard models. In this regime, properties such as density, viscosity, thermal conductivity, and specific heat vary strongly with temperature and pressure, and real-fluid equations of state are required for common fluids like hydrogen, LNG, ammonia, or ethylene. These models introduce numerical stiffness and make convergence more difficult, especially when steep gradients form at liquid-vapour interfaces. Heat transfer is equally complex because small thermal fluctuations can trigger large mechanical responses, and turbulence models tuned for ambient conditions may fail to capture cryogenic behaviour. Under these premises, the evaluation of the physical and chemical properties determining the gas-phase reactivity in a compact but still rigorous way is paramount. These aspects can be covered by means of direct assessment of the overall reactivity, expressed in terms of the laminar burning velocity, as well as integrating kinetic mechanisms in a reduced form. Development of detailed kinetic models at cryogenic conditions is difficult because the assumptions behind standard high-temperature chemistry break down as reaction rates, transport properties, and dominant pathways shift in ways classical formulations cannot properly tackle. For instance, at extremely low temperatures, Arrhenius expressions become unreliable since quantum tunnelling allows reactions with sizable activation barriers to proceed, yet incorporating accurate tunnelling corrections or quantum-derived rates is computationally demanding and often limited by scarce data. Thermodynamic consistency also becomes problematic because equilibrium constants and species properties fitted at higher temperatures behave unphysically when extrapolated downward, as illustrated by the ortho–para hydrogen imbalance that distorts macroscopic thermodynamics if not treated correctly. Reaction networks themselves may be incomplete, since low-temperature chemistry favours barrierless channels, radical recombination, and three-body processes that are negligible at higher temperatures but dominant in the cryogenic regime. Transport properties further complicate modelling because diffusion, collision frequencies, and energy-transfer rates depend on intermolecular potentials that change qualitatively at low thermal energies, making simplified collision models inadequate.

Considering the theoretical nature of the discussed numerical approaches, a validation step is highly desirable. However, validation remains the main limitation since experimental data at cryogenic temperatures are extremely scarce and difficult to obtain, promoting the realization of experimental systems and protocols suitable for the investigated conditions. Other than the main concepts and working principles of existing experimental systems, elements of the temperature control systems were discussed in view of their possible utilisation at extremely low temperatures for the sake of accurate analyses of cryogenic processes and fluids. While numerous techniques provide reliable data under ambient conditions, their transferability to low-temperature operation is limited by increased heat losses, thermal inhomogeneities, buoyancy effects, flame stretch sensitivity, and condensation risks. For LBV measurements, classical Bunsen burner and spherical flame methods become increasingly sensitive to curvature, wall interaction, and stabilization effects at low temperatures. Counterflow burners offer well-defined flame structures but require complex thermal control to ensure reproducible inlet conditions. Wall-dominated configurations are unsuitable due to amplified quenching and conductive losses. Among the evaluated systems, the heat flux burner appears most promising for cryogenic adaptation, as its quasi-adiabatic flat-flame configuration allows controlled thermal boundary conditions and systematic cooling integration. The first outcome deriving from the presented elements was the identification of the systems showing the highest potential to achieve a stable and steady state flame, suitable for the characterisation of flame behaviour at low temperatures. Nevertheless, none of the existing methods is currently able to properly account for the peculiar physical and chemical phenomena relevant at cryogenic temperature (e.g., non-ideal gas behaviour, condensation, non-uniform velocity field), calling for design modifications and materials adaptations.

For MIE determination, capacitive spark systems in controlled burner geometries have demonstrated feasibility down to cryogenic temperatures, whereas large explosion vessels and transparent chambers require significant modifications in thermal management and sealing technology. Across all methods, accurate energy quantification, prevention of phase change, and strict temperature homogeneity are critical. In summary, LBV and MIE measurements at cryogenic conditions are technically feasible but experimentally demanding. Reliable data require integrated thermal management, precise mixture conditioning, and rigorous control of systematic uncertainties.

CRedit authorship contribution statement

Gianmaria Pio: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Ernesto Salzano:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Sven Eckart:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

At the time of final publication all of the authors are members of the Editorial Board. Further, the authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge funding by the European Union under the Horizon Europe project *CESAR – Centre of Excellence for Safety Research* (Grant Agreement No. 101186946).

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