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INFLUENCE ON THE USE OF KEROSENE AND PROPANE AS FUELS ON CHARACTERISTICS OF IN-FLIGHT PARTICLES DEPOSITED BY THERMAL SPRAY HVOF

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Abstract. *The measurements of in-flight characteristics, such as temperature and velocities sprayed by different HVOF torches, using FeMnCrSi powders spherical shaped were carried out. It was found that the three types of torches were capable of depositing coatings with a homogeneous morphology. It was possible to realize that the velocity and temperature can be controlled by adjusting the flow rates and consequently stoichiometric ratio. There is, therefore, a more accentuated difference in the temperature of in-flight particles, with the kerosene gun reaching the highest speeds. That could change the morphology with greater deformation of the splats, and elevated kinetic energy. In conclusion, the adopted experimental planning allowed mapping of the influence of the parameters, making it possible to understand the relationship that the quality of the coatings has with different deposition conditions.*

Keywords: *HVOF, thermal spray, propane-fueled, kerosene-fueled, DPV*

1. INTRODUCTION

Thermal spray technology is commonly used for protection and to improve the durability of equipment, especially those imposed by harsh environments, such as wear and corrosion. The High Velocity oxy-fuel (HVOF) thermal spraying is a technique that provides combustion, which is burned and the products are accelerated through a convergent-divergent nozzle. This mechanism makes the powder particles to be injected by a carrier gas in high velocities, creating a supersonic flame.

The demand for quality coatings requires reliable methods to monitor and optimize the spraying process. The DPV-2000 was used in this work. This equipment enables the measurement of particle velocities and temperature. The velocity is obtained by the difference in time between the two signals, triggered by a radiating particle passing through the sensor head. The temperature is acquired by two-color pyrometry, being necessary to know the real emissivity of the particle and, therefore, a prior calibration is needed. (Mauer et al., 2007)

Both fuels used in thermal spray torches, conducted in this research, presents different characteristics. Propane has increased calorific values in relation to kerosene, and a cleaner combustion considering release of pollutants and greenhouse gases. Therefore, propane is a better choice, considering these technical features. Besides, it is important to analyze differences between these techniques that are fully studied.

Mathematical modeling of the processes was carried out by Li et al. (2021), Kamnis & Gu (2006a) and Kamnis & Gu (2006b). According to Liu (2022), the HVOF process can generate flames at moderate to high temperatures exceeding 3000°C, with high velocities above 2000 m/s. The difference in the torches is related to the type of fuel and consequently where the powder is injected, the cooling, the design of the combustion chamber, the design of the burner and the exit nozzle geometry. (Rusch, 2007)

Perhaps the most striking finding is the operating characteristics for gas as liquid fuel torches, research developed by Rusch (2007), the study has analyzed oxygen to fuel ratio and thermal efficiency; showing that the torches have similar operating and design characteristics regarding velocity. For thermal efficiency and fuel required, the design of the torches is directly related, not by the selection of fuel.

This study aims to analyze the stoichiometric ratio and different technologies of thermal spray torches in the velocity and temperature of particles. Given the influence of various fuel combustion processes on temperature and velocity, it becomes imperative to recognize their consequential impact on the obtained coating, particularly within the context of the analyzed parameters.

2. METHODOLOGY

2.1 Material

The chemical composition of the FeMnCrSi alloys is described in Table 1, the material is part of an R&D project of Copel Geração e Transmissão S.A., an electric power generation company, in cooperation with UTFPR and LACTEC.

The feedstock powder used was produced by a gas atomization process in an argon atmosphere; the powder had a round morphology with some satellite particles. An ALD Vacuum Melting Induction System equipment (Hanau, Germany) localized at the University of Clausthal (Clausthal-Zellerfeld, Germany) was used to produce the powders.

Table 1. Chemical composition of FeMnCrSi alloys in weight %

	Mn	**Cr**	**Ni**	**Si**	**N**	**C**	**Fe**
FeMnCrSi 0.5B	19.0	12.0	7.5	4.5	0.3	0.2	Bal.

The average particle size was distributed as follows in Table 2, the values of the d10 represent the 10% of particles that are below the indicated result, as well as d50, 50% and d90, 90%.

Table 2. Particle distribution of the powders %

	d10	**d50**	**d90**
FeMnCrSi 0.5B	15 µm	30 µm	45 µm

2.2 Experimental setup

The thermal spray process used was a kerosene-fueled HVOF; the deposition was carried out with a robot system, and a propane-fueled HVOF. Figure 1 and Figure 2 show a schematic illustration of both processes and signal sensing head used to analyze velocities and temperature of in-flight particles.

The parameters used are listed in Table 3 and Table 4.

Table 3. Parameters used for kerosene-fueled HVOF

Samples	**Distance (m)**	**Oxygen flow (l/min)**	**Kerosene flow (l/min)**	**Feed rate (g/min)**	**Stoichiometry**	**Gas Mass flow (g/s)**
1	0.250	840	0.404	20	1,1	25.59
2	0.250	840	0.404	35	1,1	25.59
3	0.250	840	0.316	20	1,4	24.47
4	0.250	840	0.316	35	1,4	24.47

Table 4. Parameters used for propane-fueled HVOF

Samples	**Distance (m)**	**Oxygen flow (l/min)**	**Propane flow (l/min)**	**Feed rate (g/min)**	**Stoichiometry**	**Gas Mass flow (g/s)**
5	0.250	260	52	50	1,0	7.88
6	0.250	161	58	50	0,55	5.72
7	0.250	200	52	50	0,75	6.46

The kerosene-fueled HVOF process was realized using equipment commercially available JP5000, and the propane-fueled HVOF process used equipment also commercially available DJ2600. The temperature and velocity of in-flight particles were measured with DPV-2000 for 1-4 samples and AccuraSpray for 5-7. The equipment AccuraSpray provides ensemble average data, representing the particle characteristics. (Mauer et al., 2007)

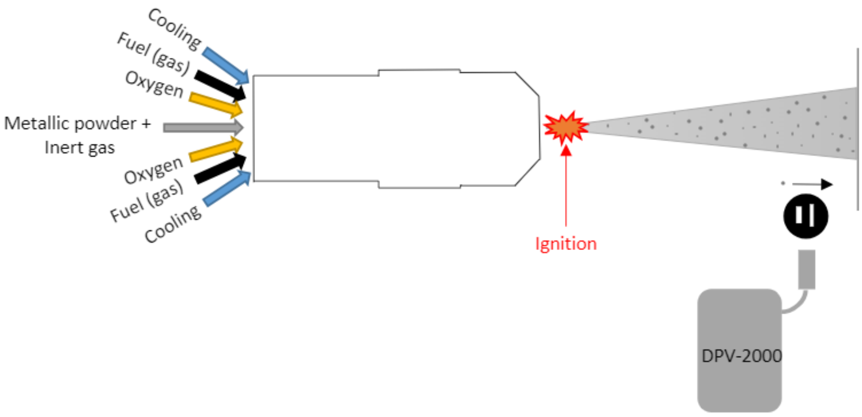

Figure 1. Schematic illustration of the HVOF propane-fueled DJ2700 torch and signal sensing head.

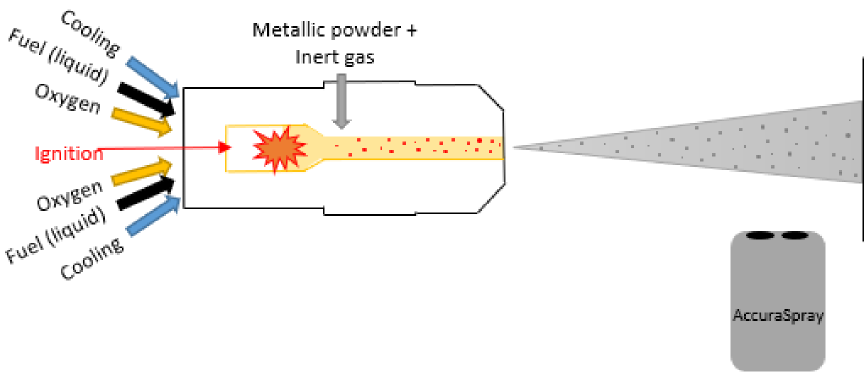

Figure 2. Schematic illustration of the HVOF kerosene-fueled JP5000 torch and signal sensing head.

The stoichiometry, represented by λ, was calculated by oxygen and kerosene flow for kerosene-fueled HVOF and by oxygen and propane flow for propane-fueled HVOF. As demonstrated in Eq.1 and Eq. 2.

The kerosene ($C_{11}H_{21}$) stoichiometry equation is

$$C_{11}H_{21} + 16.25\ O_2 \rightarrow 11\ CO_2 + 10.5\ H_2O \tag{1}$$

For kerosene, the density of aviation kerosene ($C_{11}H_{21}$) used was 803 kg/ m^3, and the molecular mass used was 153u. Therefore, obtaining a ratio between the oxygen flow and kerosene flow 1910.4, for a stoichiometry relation of one. For stoichiometries different from one, a percentage was applied to the molecules of oxygen in the chemical reaction.

The propane (C_3H_8) stoichiometry equation is

$$C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O \tag{2}$$

Therefore, the stoichiometric ratio between oxygen and propane is five. The molar volume corresponding to the volume occupied by the gas, in the NTP (Normal temperature and pressure conditions), is equal to 22.4l. Using this value and multiplying by the number of molecules of the stoichiometric reaction will obtain the value in liters. Since both are gases, the ratio between the oxygen flow and propane flow will remain five, for a stoichiometry relation of one.

The stoichiometry and mass flow were calculated and used to form Figure 3 and Figure 4, to relate the deposition with a deposition window. The mass flow rate was determined by multiplying the densities of oxygen and fuel with their respective flow rates and adding them together.

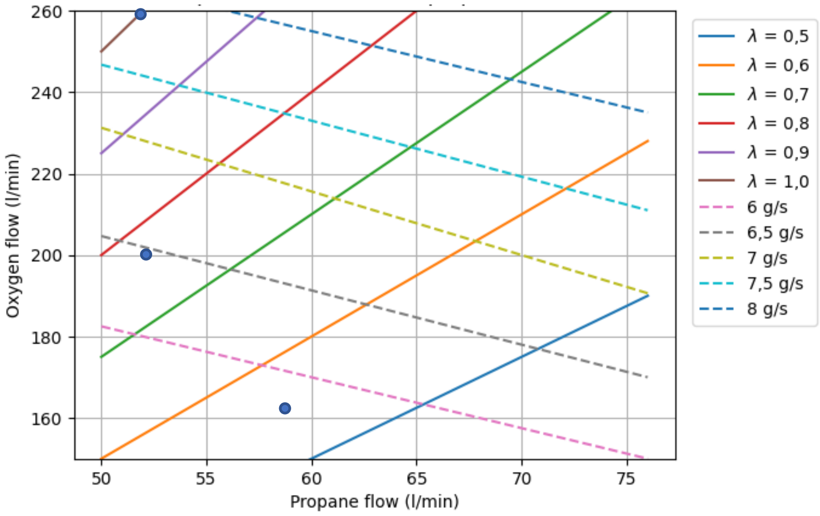

Figure 3. Deposition window of HVOF propane-fueled.

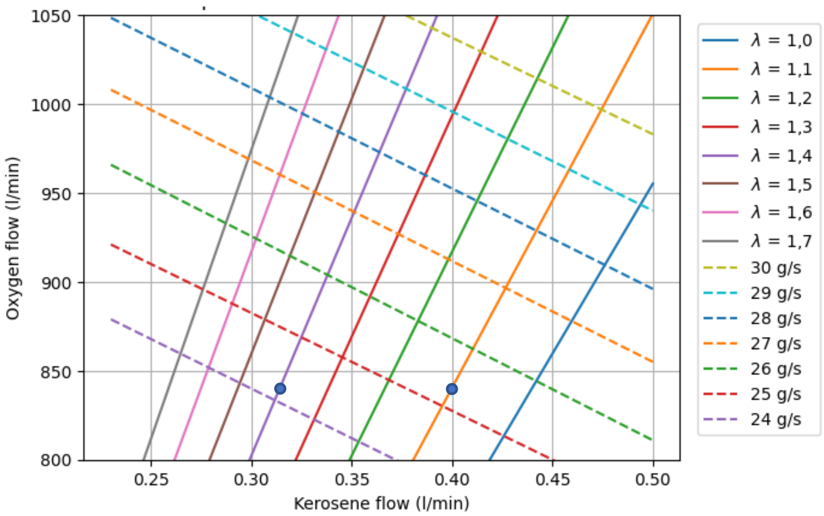

Figure 4. Deposition window of HVOF kerosene-fueled.

The use of the deposition window is justified by its ability to provide a clear visualization of the dynamic relationship between the fuel/oxidizer gas flows and their volume. This allows for an interpretation of this relationship beyond just a percentage mixture of gases, as this window enables the observation of both the proportional mixture of gases (stoichiometry) and the quantity relationship in mass. In the flow meters of thermal spray equipment, gas flow is regulated in liters per minute or cubic feet per hour, but the physical characteristics of combustion (temperature and projection velocity) depend not only on stoichiometry but also on the quantity of gases being supplied in grams per second. Therefore, through the analysis of the deposition window, it is possible to maintain a necessary and consistent quantity of gases for comparing a specific stoichiometric proportion.

3. RESULTS AND DISCUSSION

In Figure 5 and Figure 6, the general results of temperature and particle velocity measurements during flight are depicted for both kerosene and propane in HVOF systems. Figure 5 illustrates a notable disparity in particle acceleration between the kerosene and propane applications.

The kerosene-fueled gun exhibits significantly higher particle velocities compared to the propane counterpart. This notable discrepancy arises from the substantial disparity in gas flow rates, with the kerosene model processing a volumetric flow rate of approximately 25g/s, while the propane model operates at a significantly lower rate of 6g/s. Therefore, the temperature variation for propane is greater due to the lower velocity, allowing the particles to be exposed to the heat source for a longer period of time.

The observed variation in gas flow volume is attributed to the requisite stoichiometric quantity for combustion. It is noteworthy that the stoichiometric combustion of kerosene requires an oxidizing flame due to the toxic byproducts resulting from its incomplete combustion, which may result in tissue inflammation and oxidative stress or even the deposit of particulate matter in the deep lungs, increasing the risk of respiratory diseases. (Maiyoh et al., 2015)

Figure 6 displays the comparable particle heating capacity between the two fuel types, with the primary distinction lying in the observed temperature range. Notably, the average particle temperature remains unaffected by the choice of fuel.

According to (Kamnis & Gu, 2006a) who extensively investigated the temperature at the gun exit, the average temperature recorded for kerosene combustion was 2100°C. Thus, the average temperature is close to 2000°C, regardless of the heat source. Despite the variation in parameters and, consequently, the variation in stoichiometric ratio, the temperature of the particles remains constant.

The calorific value of both fuels is similar (kerosene: 11.94 kWh/kg (*Aviation Fuels: Technical Review*, 2007) and propane: 12.88 kWh/kg (Moran & Shapiro, 2002)), which explains the similar average temperature. However, propane shows a slightly higher temperature due to the higher observed standard deviation.

In addition, as illustrated in Figure 6, it is possible to notice that the equipment AccuraSpray provides average data, and that was related to the low standard deviation, especially compared to the data obtained with DPV-2000. Both Accuraspray and DPV are widely employed sensors for this analysis, and as reported by (Colmenares-Angulo et al., 2011), the measurement trends were consistently observed across both sensor types.

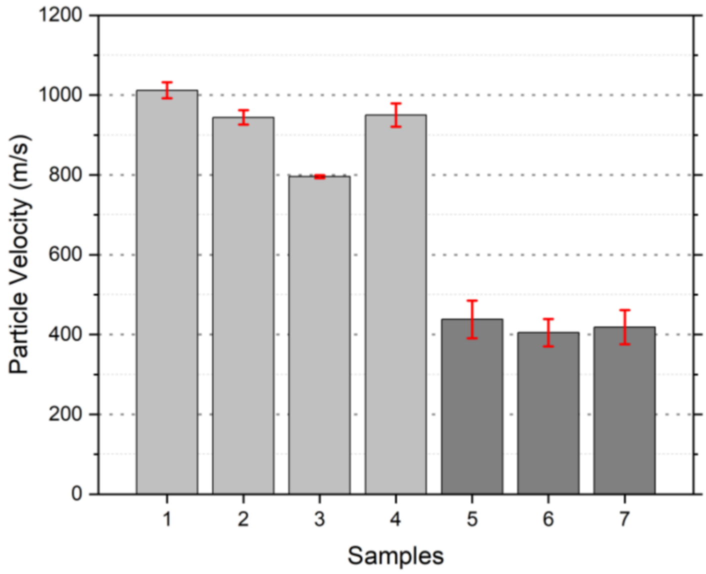

Figure 5. Average particle velocity of each sample, including the standard deviation.

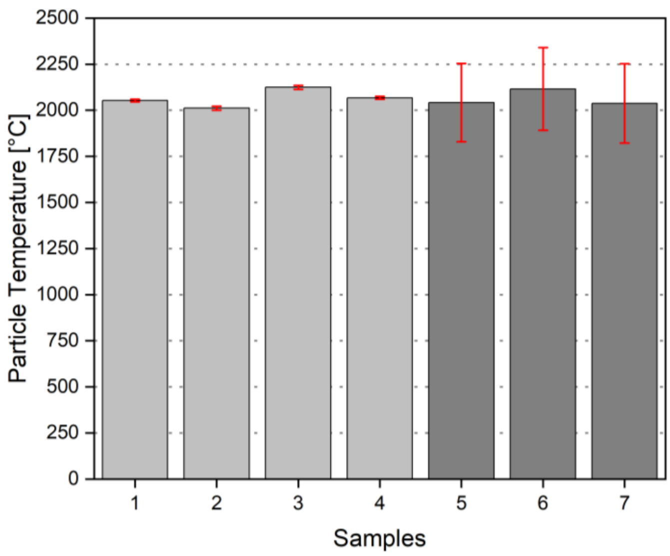

Figure 6. Average particle temperature of each sample, including the standard deviation.

Figure 7 and Figure 8 evidence that the average particle velocity increases with a stoichiometric relation near 1.0, that is the complete combustion, and that the HVOF propane-fueled has a lower speed, compared to the liquid-fueled process. Whilst for the average particle temperature, there is not a significant influence.

For a stoichiometry of 1.4, the particle velocity decreased, as the experiment considered only the reduction in kerosene flow rate, consequently reducing the total mass flow rate, which impacts the reduction in velocity. In general, the variation in stoichiometry does not generate a huge variation in the temperature reached by the particles, regardless of the fuel used.

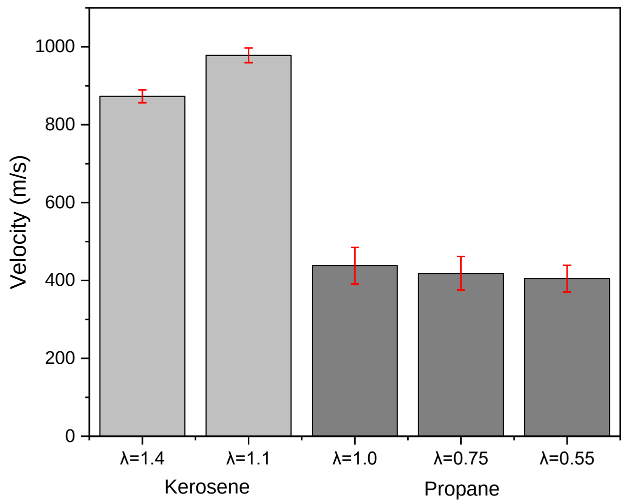

Figure 7. Particle velocity at different stoichiometric ratios.

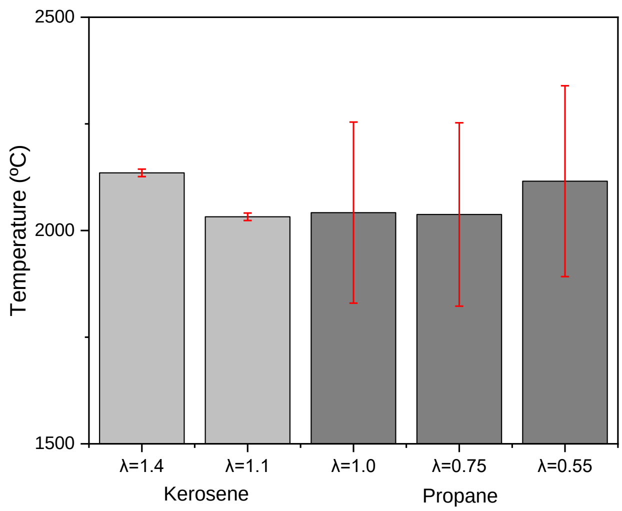

Figure 8. Particle temperature at different stoichiometric ratios.

For coatings of austenitic stainless steel alloys susceptible to deformation-induced transformation, as is the case with the alloy employed in this study (FeMnCrSi), it is observed that the combination of higher velocities and temperatures, without significant increments, yields a structurally high-quality coating (low porosity). However, this also results in a greater presence of martensitic phase due to deformation-induced transformation.

According to a recent investigation conducted by (Liu et al., 2023), varying the stoichiometry in liquid fuel thermal spray torches, such as ethanol, has minimal influence on the phase composition of coatings. However, it has a significant impact on their microstructure and properties, including factors such as porosity, micro-hardness, and fracture behavior, among others. These findings highlight the significance of comprehensively studying the stoichiometric ratio in the context of this particular technological domain.

4. CONCLUSION

The study findings revealed that the stoichiometric analysis of the various thermal spray torches did not exhibit significant temperature fluctuations. However, deviations from a stoichiometry of 1.0 were observed, indicating incomplete combustion. It's important to note that an increase in the amount of oxidation leads to an increase in temperature, as oxidation is exothermic. In terms of velocity, variations were observed across the different processes.

Notably, the kerosene torch exhibited higher velocities, which directly correlated with the total mass flow of the combustion mixture. "Kerosene deposits also lead to coatings exhibiting a higher degree of work hardening, consequently enhancing their hardness."

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Aviation Fuels: Technical Review, 2007. Chevron Products Company, skybrary.aero/sites/default/files/bookshelf/2478.pdf. Accessed 10 October 2023.

Colmenares-Angulo, J., Shinoda, K., Wentz, T., Zhang, W., Tan, Y., & Sampath, S., 2011. “On the response of different particle state sensors to deliberate process variations”. *Journal of Thermal Spray Technology*, Vol. *20*, p. 1035.

Kamnis, S., & Gu, S., 2006a. “3-D modelling of kerosene-fuelled HVOF thermal spray gun”. *Chemical Engineering Science*, Vol. *61*, p. 5427.

Kamnis, S., & Gu, S., 2006b. “Numerical modelling of propane combustion in a high velocity oxygen-fuel thermal spray gun”. *Chemical Engineering and Processing: Process Intensification*, Vol. *45*, p. 246.

Li, C., Gao, X., Zhang, D., Gao, H., Han, X., & Zhang, B., 2021. “Numerical Investigation on the Flame Characteristics and Particle Behaviors in a HVOF Spray Process Using Kerosene as Fuel”. *Journal of Thermal Spray Technology*, Vol. *30*, p. 725.

Liu, S., 2022. *Optimization and Improvement of a Novel HVOF Process Fueled with Ethanol*. Ph.D. thesis, Université Bourgogne Franche-Comté, Besançon, France.

Liu, S., Wu, H., Xie, S., Yu, Z., Luo, H., Yazdi, M. A. P., Planche, M. P., Moliere, M., & Liao, H., 2023. “Effect of stoichiometry conditions on the erosion and sliding wear behaviors of Cr3C2-NiCr coatings deposited by a novel ethanol-fueled HVOF process”. *Surface and Coatings Technology*, Vol. *454*, p. 129084.

Maiyoh, G. K., Njoroge, R. W., & Tuei, V. C., 2015. “Effects and mechanisms of kerosene use-related toxicity”. *Environmental Toxicology and Pharmacology*, Vol. *40*, p. 57.

Mauer, G., Vaßen, R., & Stöver, D., 2007. “Comparison and applications of DPV-2000 and accuraspray-g3 diagnostic systems”. *Journal of Thermal Spray Technology*, Vol. *16*, p. 414.

Moran, M. J., & Shapiro, H. N., 2002. *Fundamentals of Engineering Thermodynamics (in Portuguese)*. Editora LTC, Rio de Janeiro.

Rusch, W., 2007. “Comparison of Operating Characteristics for Gas and Liquid Fuel HVOF Torches”. *Combustion*, p. 572.

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