Erosion and heating of polyurea under cavitating jets

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ABSTRACT
Earlier observation of cavitation erosion of polyurea coatings has shown that failure is due to synergetic effects between the locally imparted impulsive loads and heating of the material. Both result from the interaction between large amplitude cavitation bubble dynamic and material response and deformation. In order to investigate this interaction and quantify damage and heat generation in the material subjected to cavitation, cavitating jet tests were conducted on polyurea coated samples while measuring both the erosion of the polyurea and the temperature evolution. The effects of polyurea composition, cavitation field intensity, material of the substrate, and thickness of the polyurea coating on the erosion and temperature were deduced from the tests.

1. Introduction
Cavitation in a liquid occurs when the local pressure drops below the liquid vapor pressure (e.g. due to high local velocities) leading microscopic bubble nuclei to grow and then collapse violently [1,2]. The successive violent collapse of a multitude of bubbles in a cavitating field generates repeated impulsive loads on the material surface, which could result in material local failure and cavitation erosion. A recent comprehensive description of the state-of-art experimental and numerical techniques to investigate the physics of cavitation erosion can be found in [2-4]. Cavitation damage is a problem in turbomachinery such as pumps, propellers and impellers, and protection of the material surface by polymeric coating can be an approach to delay substrate deterioration and avoid to have to replace parts. The general wear characteristics of these coating have been studied [5,6], and reported cavitation erosion studies include erosion of polymers [7], non-metallic coatings [8], epoxy resins and coating layers [9,10], ultra-high molecular weight polyethylene [11], various coating materials used in ships [12], and polyurea coatings on hydraulic concrete structures [13]. Coatings are also been applied more often on ship hulls and propellers as anti-fouling, drag reducing, and/or energy saving aids [14-17], and it is now important to further understand their resistance to cavitation. Cavitation erosion tests in [18] demonstrated that the temperature rise of plastic specimens subjected to cavitating flows was an order of magnitude higher than for metals, such as aluminum and stainless steel. Substantial work in this field is still required to provide a better understanding of the cavitation erosion mechanism of polymeric materials and to guide the development of more erosion resistant coating materials.

Amongst many polymeric materials, polyurea is of particular interest due to its reported good performance as a reinforcement of metal structures against shocks from blast and impact loads [19]. In addition, polymers with urea bonding involve faster reaction time than those associated with polyurethane and this fast reaction time enables the desirable spray process of polyurea coating applications. Experiments characterizing the material properties of polyurea have been conducted under a range of different strains and strain rates [20-23]. The experiments indicate that polyurea is sensitive to strain rate, i.e. there is a rubbery-to-glassy transition in the material response as the strain rate is increased. It is also known that the rheological and yield properties of polymers are highly sensitive to temperature.

We have already reported cavitation erosion experiments on polyurea and the effects of polyurea coating thickness, composition, and temperature on the cavitation erosion in [24]. This study showed that the damage was in the form of a crater with a strong evidence of plastic flow. Some data suggested that thinner coating resisted cavitation better than a thicker coating. The studies also showed that the material resistance to cavitation erosion increased significantly at low temperatures and numerical simulations explained this behavior by the heat generation in the viscoelastic material when it is exposed to repeated microscopic bubble collapse loading [25]. As the temperature increases, the material shear modulus drops dramatically, followed by material plastic flow and large crater shape deformation.

Examples of cavitation damage produced by a cavitating jet translating over a 1 mm thick polyurea coating on an aluminum substrate is shown in Fig. 1. As we discuss in further details in the paper, the jet was
translated in order to reduce the heat accumulation obtained with stationary jet experiments. In absence of translation and at sufficiently intense cavitation (large jet speeds or nozzle pressure), the material fails as shown in Fig. 2. Both figures show evidence of plastic flow of the material caused by the softening of the polyurea. The failed polyurea can be seen initially to not be removed from the sample but to instead come out of the path of the cavitation and to be extruded on the edges of the region where the loads were applied. This is due, as we will see below, to poor conductivity of the viscoelastic material and measurable temperature rise.

In an effort to understand this heat generation and its relation to the intensity of the cavitation field, this paper presents systematic experiments where both the level of cavitation and temperature were measured. Relations between the temperature rise, the cavitating jet pressure, the measurement radial location away from the jet axis, the thickness and composition of the polyurea coating, and the material substrate were investigated. Correspondence of the cavitation intensity used in the present study to those encountered in hydrodynamics applications is illustrated in Fig. 3. Extensive studies conducted in [2] and recently summarized in [4] have shown that all cavitation fields (e.g. in hydrodynamic fields, cavitating jets, ultrasonic devices) can be universally characterized by a normalized distribution of cavitation impulsive pressures, \( \text{n}_{\text{impulse}}(P_{\text{impulse}}) \), where \( \text{n}_{\text{impulse}}(P_{\text{impulse}}) \) is the number of impulsive pressures of amplitude \( P_{\text{impulse}} \). Each field has a characteristic, \( N^* \) and \( P^* \), which renders the normalized plot of \( \text{n}_{\text{impulse}}(P_{\text{impulse}}) \) unique. Fig. 3 shows how \( N^* \) and \( P^* \) vary with the cavitation intensity. It is seen that cavitation jet pressures less than 10 MPa correspond to laboratory tests of cavitation in a hydrodynamic channel setup.

2. Polyurea samples for temperature measurements

Two types of Polyurea samples were used in this study: circular samples molded in a Plexiglas substrate and rectangular samples formed on top of an aluminum block substrate. The circular sample was made of a 6 mm thick Plexiglas with a circular cavity measuring 25.4 mm in diameter and 2 mm deep which held the polyurea. The polyurea was prepared by the University of Massachusetts at Lowell by using various mixtures of Isonate 1431 and Versalink [19]. Underneath the polyurea, a PVDF sensor was embedded on the Plexiglas substrate and was used for pressure measurements. These are not specifically discussed in this paper but were addressed in previous work [24,25].

To measure the temperature distribution at various radial distances from the cavitation jet axis, four K-type thermocouples (Omega® Model No. 5SC-KK-K-30-36) were implanted at 2.5 mm intervals along a straight line (Fig. 4a), with the first thermocouple positioned directly under the axis of the jet. The thermocouples were installed from the bottom of the sample through holes made in the substrate (Fig. 4b). After inserting the thermocouples, the holes were sealed with silicon adhesive E6800 to prevent contact of the sensitive parts of the thermocouple with the surrounding water. The temperature was obtained using a Thermocouple-to-Analog Converter (Omega® SMC-J). The effective measurement range for this unit is from \(-148\) °F to \(+2282\) °F with an accuracy of \(\pm 4\) °F. Additionally, measurements were also taken at different depths to observe the distribution of the temperature through the thickness of the material.

The rectangular polyurea samples had various thicknesses and had 12.5 mm thick aluminum or Plexiglas substrates. Three types of Polyurea were tested: P-1000, P-650 and a Blend of the two. All three formulations are combination of Isonate 1431 and an Amine: PU-1000 uses VP1000 for the amine, PU-650 uses VP650, and the blend uses a 76:24 wt ratio of a mixture of VP1000 and VP650. The length of each sample was 102 mm (4 in.) and the width was 51 mm (2 in.). Table 1 lists the samples that were used in the tests reported in this paper.

3. Experimental setup and procedures

3.1. Stationary jet tests

The cavitation jet erosion test facility used in this work is a flow loop, which is composed of a CAVIJET® nozzle, a sample holder, a test tank, a water reservoir, and a pump capable of generating 1200 psi (8.3 MPa) at a flow rate of 5 gpm (19 l/min). Fig. 4 shows a photograph of the flow loop. The cavitation erosion tests were conducted utilizing cavitating jet nozzle with the orifice diameter of 0.086 in. (2.2 mm) (Fig. 5). The CAVIJET® nozzle induces cavitation in the submerged jet shear layer initiated from a sharp corner at the orifice exit to produce extremely high, localized stresses on a surface due to cavitation bubble collapse near the jet stagnation region on the sample. The cavitation generated by a cavitating jet provides realistic cavitation bubble clouds with distribution of various size micro bubbles, which then collapse on the test material surface.

Fig. 6 shows the 2-mm thick circular polyurea P-650 sample poured into a recess in a 2 in. by 2 in. (5.08 cm x 5.08 cm) square Plexiglas block positioned in the sample holder inside the test chamber. The sample holder ensures that the sample is maintained in place during the test and can be returned to the same position between successive measurements and observations. The sample was placed at a standoff distance of 1 in. (2.54 cm) from the nozzle exit, and the cavitating jet from the nozzle impinged perpendicularly on the sample surface. All
the tests in the study were conducted with fresh tap water at room temperature. In order to avoid damage to the polyurea and the thermocouples by the cavitating jet during the temperature measurement experiments, the tests were conducted at relatively low pressures in the range 300–500 psi (2–3.5 MPa). (Fig. 7)

The procedure for each test condition was as follows:

1) The temperature of the sample prior to the experiment was recorded for one minute before turning on the cavitating jet.
2) The cavitating jet was then turned on, and the sample was exposed to the cavitating jet for five minutes.
3) After the five minutes, the cavitating jet was stopped.
4) The temperature was monitored for additional four minutes to record the cooling of the material.

This is illustrated below in the paper is several figures, for example in Fig. 11.

### 3.2. Translating jet tests

The translating jet cavitation test is an innovative cavitation erosion test setup, which we have developed. It uses computer-controlled means to specify the jet pressure and to translate the cavitating nozzle over the test sample. It can be used to determine the resistance of materials to cavitation erosion over a range of cavitation load conditions. The nozzle is mounted on an X-Y translation table powered by two step motors which can be programmed to move the nozzle following a prescribed trajectory (Fig. 8). A metering valve controlled by a programmable electric actuator is used to control the pressure driving the nozzle flow. During the erosion tests presented here, the pressure was varied between two specified values while the jet was translated at a constant (but variable from test to test) translation speed. In this way, the coating samples were tested to determine the threshold pressure and translation speed which delimit the region where the material fails.

The translating jet setup was also used to obtain the temperature response of the material with the jet translating over a thermocouple implanted in the polyurea at different translation speeds. Fig. 8 shows a sketch of the polyurea sample with a thermocouple inserted in the middle of the sample. The temperature was recorded as the cavitating jet as the cavitation region passes over the thermocouple. Time history of the temperature was recorded for further analysis. (Fig. 9)

### 3.3. Measurements accuracy and repeatability

The accuracy of the various instrumentation used to generate the data shown below is as follows. All temperatures measured with the K-type thermocouples had an accuracy of ± 4ºF. The response time of the thermocouples was 0.25 s. All jet pressure measurements were ± 2% of the gauge full range, which resulted in pressure readings with an accuracy of ± 2%.

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**Fig. 3.** Characteristics of the cavitation intensity for different pump pressure: a) Characteristic impulsive pressure height and b) Characteristic number of cavitation pulses.

**Fig. 4.** (a) Top view of the circular polyurea sample. Cavitating jet impinges on top of the thermocouple near the center of the circle. The thickness of the polyurea is 2 mm and the PVDF sensor is below the polyurea at the interface with the Plexiglas. (b) Detail of the thermocouple insertion in the polyurea sample.
The accuracy of ± 30 psi (0.2 MPa). Depth and measurement accuracy was ± 0.03 mm, while jet positioning relative to the thermocouple was with an accuracy of 1 mm.

Prior to conducting the tests presented below, repeatability of the studied process was investigated for instance on a static jet impacting the polyurea sample. The maximum temperature increase under the cavitating jet was repeatedly measured under the jet at different probe positions from the axis of the jet. Fig. 10 shows the decay of the maximum temperature rise achieved with distance from the jet axis. Represented are the average values and the standard deviations. Similar repeatability of the data applies to the figures shown below. However, we have shown on some of the figures the accuracy of the instrument used for the measurements.

4. Temperature rise under cavitating jets

4.1. Effect of jet cavitation intensity on temperature

The intensity of cavitation in a cavitating jet can be expressed by the cavitation number defined as:

\[
\sigma = \frac{P_{\text{amb}} - P_v}{0.5 \Delta P_{\text{jet}}} \approx \frac{P_{\text{amb}} - P_v}{\Delta P},
\]

where \(P_{\text{amb}}\) is the ambient pressure where the sample is located, \(P_v\) is the vapor pressure, and \(\Delta P\) is the pressure drop across the nozzle. Cavitation occurs in flow conditions where \(\sigma\) is lower than the cavitation inception value, \(\sigma_{\text{inc}}\), and, generally, the cavitation intensity increases as \(\sigma\) decreases, i.e., as \(\Delta P\) increases.

Temperature measurement experiments under a static nonmoving cavitating jet were conducted at pressures \(\Delta P\) ranging from 300 psi to 500 psi (2–3.5 MPa); values where cavitation was intense but not strong enough to permanently damage the samples or the thermocouples during the tests. The substrate of the samples described in this section was Plexiglas. Fig. 11 shows the evolution over time of a) the temperature and b) the temperature rate.

The initial temperature, \(T_0\), was recorded prior to the test and was the same as the water temperature in the test tank. This was recorded during the first 1 min (Fig. 11a). When the cavitating jet was turned on (at \(t = 1\) min), the temperature in the polyurea rose very sharply attaining temperature change rates of 8, 21, and 42° F/min for the 300, 400, and 500 psi (2 MPa, 2.75 MPa, 3.5 MPa) jets respectively (Fig. 11b). The rate then dropped almost exponentially and the temperature rise, \(\Delta T\), reached a plateau, \(\Delta T_{\text{max}}\), after about 3 min when the heat generation in the viscoelastic material and the heat dissipation through conduction became in equilibrium.

When the cavitating jet was turned off at \(t = 6\) min, the inverse phenomenon occurs. The polyurea cooled down exponentially starting with a very high initial rate (see Fig. 11b), and within a couple of minutes the temperature returned to the ambient temperature. The final temperature ended a couple of degrees F higher than the initial temperature due to the gradual warming of the water temperature in the test tank during the test. The overall temperature rise of the water was up to 2° F for the case of the highest pressure, 500 psi (3.5 MPa) (Fig. 11a).

Fig. 11a clearly shows that the maximum temperature reached increases significantly with the jet pressure. The highest temperature rise, \(\Delta T_{\text{max}}\) with the 500-psi (3.5 MPa) jet is 32° F, while it is about 15° F for the 400-psi (2.75 MPa) jet, and only about 5° F for the 300-psi (2 MPa) jet. Fig. 11b shows the same trend for the rates of temperature change, which attains a maximum of the order of 42° F/min with the 500-psi (3.5 MPa) jet and only about ~ 8° F/min for the 300-psi (2 MPa) jet. Fig. 12 consolidates the temperature results and shows the maximum

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**Table 1**

<table>
<thead>
<tr>
<th>Compositions</th>
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<th>Substrates</th>
<th>Shapes</th>
<th>Dimensions</th>
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<td>Plexiglas</td>
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Fig. 5. The jet cavitation erosion test loop used in this study.

Fig. 6. Sketch of the cavitating jet, CAVIJET® nozzle used in this study. Orifice diameter: 0.086 in. (2.2 mm).
temperature reached during the experiment versus the jet pressure. This illustrate a direct connection between the intensity of cavitation and the heating of the polyurea coating.

4.2. Radial and axial temperature distribution in the polyurea coating

In this section, we discuss measurements of the distribution of the temperature radially under the cavitating jet and in depth inside the polyurea coating. To do so, the temperature is monitored at different radial locations from the jet center with the thermocouples located at different depths in the coating.

4.2.1. Experimental procedures

At each location, the temperature evolved in time, qualitatively, in the same manner as in Fig. 11, rose fast, then reached a saturation maximum value temperature rise, \( \Delta T_{\text{max}} \), before the cavitating jet was turned off. Fig. 13 shows \( \Delta T_{\text{max}} \) at four different locations in the P-650 polyurea (\( r = 0, 0.1, 0.2, \) and 0.3 in., i.e. 0, 2.54, 5.08, and 7.62 mm). The highest value of \( \Delta T_{\text{max}} \) is observed on the axis, \( r = 0 \), and \( \Delta T_{\text{max}} \) decreases toward the ambient temperature as the radial distance increases, i.e. far from the cavitating jet axis. The same trend is observed for all three different pressures. This temperature distribution illustrates that the generation of heat is the most intense near the jet axis where the cavitation bubble dynamics and collapse is the most intense. Farther from there, less and less cavitating bubbles collapse and the temperature decays radially and returns to the liquid ambient temperature.

The temperature distribution in the depth direction is measured by placing the thermocouples at different depths from the polyurea-water interface. The results depend strongly on the substrate. Here, we consider two different substrate materials, Plexiglas and Aluminum. Very different cavitation erosion performance was also observed between these two substrate materials [24,25]. This difference in behavior is related to the different heat conduction characteristics of the two substrate materials. For instance, the thermal diffusivity of the two materials differ by three orders of magnitude:

- Aluminum: \( \alpha = 9.7 \times 10^{-5} \text{ m}^2/\text{s} \). [26]
- Plexiglas: \( \alpha = 1.1 \times 10^{-7} \text{ m}^2/\text{s} \). [27]

4.2.2. Plexiglas substrate

In this Section, 2 mm thick P-650 polyurea were used for the tests. Fig. 14 shows the radial distribution of \( \Delta T_{\text{max}} \) at different distances (depth), \( d \), from the polyurea-water interface for three pressures: 300 psi, 400 psi, and 500 psi (2 MPa, 2.75 MPa, and 3.5 MPa). At all three pressures, \( \Delta T_{\text{max}} \) goes through a maximum inside the polyurea close to the mid-thickness of the polyurea, i.e. at about \( d \approx 1 \text{ mm} \) The heating is generated by cavitation occurring near the interface water / polyurea and the strain energy (integral of force times the deformation) deposited in the material is the highest at the interface [3,24]. However, the top surface itself sees the lowest temperature because the flowing water from the jet removes the heat rapidly. The bottom of the polyurea coating in contact with the Plexiglas substrate is able to cool moderately with some of the heat diffusing slowly though the Plexiglas. The mid-thickness of the coating results in the highest temperature as a result of these two cooling effects on the edges.
At the larger radial locations, the temperature equilibrates in the whole material thickness resulting in small temperature differences, $\Delta T_{\text{max}}$, from the initial liquid temperature. This is clear for the 400 psi (2 MPa) and 500 psi cases (3.5 MPa), where in the mid-section the temperature rises are significant: $\sim 30^\circ$ F and $\sim 65^\circ$ F respectively. Closer to the substrate the temperature changes are much smaller, $\sim 3^\circ$ F, $\sim 4^\circ$ F, and $\sim 10^\circ$ F respectively for the three pressures. For the 300-psi (2 MPa) case, these temperature rises are relatively small and in the single digits.

In Fig. 15, the maximum temperature versus the thermocouple depth is shown for the four radial locations and for the 500-psi (3.5 MPa) jet condition. This graph highlights again that maximum temperature is obtained close to the 1 mm depth for each radial location.

4.2.3. Aluminum substrate

Similar tests were also conducted with 2-mm thick P-650 polyurea on an aluminum substrate. Since aluminum has a much higher thermal diffusivity, it is expected to help much more than Plexiglas in evacuating the heat generated by the cavitation / polyurea interaction process. Indeed, as shown in Fig. 16, the maximum temperature rise, $\Delta T_{\text{max}}$, was found to be $19^\circ$ F with the aluminum substrate at 500 psi (3.5 MPa), whereas with Plexiglas substrate the corresponding temperature recorded was $63^\circ$ F. The figure shows the variations of $\Delta T_{\text{max}}$ with the location inside the polyurea for three pressures, 300, 400 and 500 psi. (1 in = 2.54 cm, 100 psi = 0.69 MPa).

For all jet pressures tested, the temperature rise was higher with Plexiglas substrate than with the aluminum substrate. With the aluminum substrate, the temperature rise decreases with the depth, i.e. with the closeness to aluminum, which evacuates the heat promptly. Due to this, the peak temperature is in this case much closer to the water polyurea interface.

The above results show that the substrate material has a strong influence on the heating of the polyurea from cavitation dynamics. This affects both the level of the temperature rise and also the location of the hottest region inside the material.
Fig. 14. Maximum temperature recorded in the 2 mm thick P-650 coating on Plexiglas as a function of radial distance from the jet axis. The standoff distance was 1 in. and the jet pressures were: a) 300 psi, b) 400 psi, and c) 500 psi. (1 in = 2.54 cm, 100 psi = 0.69 MPa).

Fig. 15. Maximum temperature recorded in a 2 mm thick P-650 coating on Plexiglas substrate. The jet pressure was 500 psi and the standoff was 1 in. (1 in = 2.54 cm, 100 psi = 0.69 MPa).

Fig. 16. Value of the maximum temperature rise, $\Delta T_{\text{max}}$, recorded in the 2-mm thick P-650 coating on aluminum substrate. The standoff distance was 1 in. (1 in = 2.54 cm, 100 psi = 0.69 MPa).

Fig. 17. Maximum temperature of P-650 at r = 0 under a 500 psi CAVIJECT with Plexiglas and Aluminum substrates. Polyurea is 2 mm thick and nozzle is at 1 in. standoff. (1 in = 2.54 cm, 100 psi = 0.69 MPa).

Fig. 18. Temperature versus time on the jet axis 1 mm deep in the 2 mm thick P-650 polyurea coating. 1” standoff and at 500 psi (3.5 MPa). (1 in = 2.54 cm, 100 psi = 0.69 MPa).
4.2.4. Further analysis of the effects of the substrate material

The above observations are further illustrated in the following comparisons. Fig. 17 shows the variations of the maximum temperature rise, $\Delta T_{\text{max}}$, with the cavitating jet pressure. It also compares the results between the Plexiglas and aluminum substrates. The figure clearly shows the increase of $\Delta T_{\text{max}}$ with the jet pressure as well as the large difference in the temperature rise between the aluminum and Plexiglas due to the much higher thermal diffusivity of the aluminum resulting in enhanced heat conduction and lower temperature inside the polyurea. This is also reflected in the characteristic response time of the polyurea to the heating. For instance, Fig. 18 shows the progression of $\Delta T$ with time for the 500 psi (3.5 MPa) cavitating jet. The initial slope of the temperature rise is the same between the two substrate materials. However, the time to reach the plateau is different.

In order to characterize better the rise time, the time derivative of the temperature as a function of time is shown in Fig. 19. The rise time, $\Delta t$, is defined here as the width of the peak measured at 20% of the maximum, $(\text{d}T/\text{d}t)_{\text{max}}$. The selection of the 20% value is arbitrary (high enough to not overestimate the duration due to the tail of the temperature decay curve and small enough to capture the time duration where the temperature change was significant); any other selection will provide the same overall trend of the results from condition to condition. The $\Delta t$ with Plexiglas substrate is longer than the $\Delta t$ with aluminum substrate. Due to the faster conduction with aluminum substrate, the equilibrium is reached quicker.

A plot of the rise time, $\Delta t$, versus the jet pressure is shown in Fig. 20. For both materials, the rise time is almost independent of the jet pressure. However, the rise time with the aluminum substrate is about three times shorter; around 15 s versus 45 s with the Plexiglas.

Fig. 21 presents the rise time as a function of the depth in the material where the thermocouple is located. We can see that the rise time increases as the depth increases. A thermocouple closer to the surface reaches steady state faster. This effect is observed for both substrates, but it is more prominent with the Plexiglas substrate, which needs more time to reach the ‘equilibrium’ when $\Delta T_{\text{max}}$ is reached.
4.3. Effects of polyurea coating thickness and composition

Practically, for substrate protection purposes, it is important to know the influence of the coating thickness on the results. In this section, we examine how the heating of the polyurea is affected by the thickness. To do so, temperature measurements were conducted on P-1000 polyurea samples with three different thicknesses: 0.5 mm, 1 mm and 2 mm. To compare the three thickness conditions, the positioning of the thermocouple in depth was selected to conserve the normalized depth by the thickness of the coating, \(h\), as follows:

\[
\bar{d} = \frac{d}{h},
\]

where \(d\) is the distance between the thermocouple and the polyurea / water interface.

Fig. 22 shows, for \(\bar{d} = 0.5\) (i.e. at mid sample thickness) the effect of the polyurea thickness on the temperature rise, \(\Delta T_{\text{max}}\). The temperature increased about 14° F in the 1.5 mm thick coating, about 10° F in the 1 mm thick coating, and only about 2° F for the 0.5 mm thick coating. This illustrates that heat dissipation through the aluminum substrate, achieve following heat conduction in the polyurea, is more efficient with the thinner coating. Since the mechanical properties of the polyurea are sensitive to the temperature, with the polyurea becoming weaker as the temperature rises (both the storage and loss moduli drop significantly when the temperature increases from 0 °C to 50 °C [28]), a thinner coating should be more resistant to cavitation erosion. This is actually consistent with our observations of the failure pressure discussed further below and is similar to observations of the heating of polyurethane coating by the impact of solid particles [29].

Three different types of polyurea samples were studied P-1000, P-650, and P-Blend. Fig. 23 shows the maximum temperature rise in these samples versus jet pressure. In all three cases, the substrate was aluminum. As expected from the measured resistance to erosion shown in Section 5, the highest temperature was obtained with the weakest blend for cavitation erosion P-1000, followed by P-650, and then by the Blend composition.

4.4. Temperature evolution during cavitating jet translation

In order to investigate transient temperature effects during translating cavitating jet erosion tests, we conducted the following...
5.1. Stationary cavitating jet erosion tests

In this section, we present cavitation erosion observations and measurements at higher jet pressures that what was used in the temperature tests, where we avoided damaging the thermocouples and tried to not modify permanently the polyurea coating during a temperature measurement test. The cavitation erosion tests reported below were conducted at a jet pressure of 800 psi on both the P-650 and P-1000 with aluminum 6061 as the substrate in the cavitating jet test loop described in Section 3.1. The water temperature was controlled within ± 1°C by adding ice to the water or heating the water. Tests measurements. The cavitating jet was made to translate over a thermocouple embedded in the polyurea sample at various translation speeds. The thermocouple was located at the center of the 4-in. sample (2 in from the starting edge of the sample) and translation speeds were varied between 0.01 in/s (2.54 mm/s) and 0.08 in/s (20.3 mm/s).

Fig. 24 shows, for 5 translating speeds, the temperature measured by the thermocouple located at a 2-in. distance from the edge of the sample, when the axis of the translation jet is at the distance r. The tested sample was 1 mm thick P-1000 with a thermocouple at 0.25 mm depth. The nozzle standoff distance was 1 in. from the surface, and the pressure was 500 psi (3.5 MPa). Until the jet traveled around 1.2 in. (3 cm) from the starting edge, the temperature remained approximately the same for all translation speeds. Then, depending on the translation speeds, the temperature increased until it reached a maximum value and then finally decreased, and stayed at a constant temperature value about 1° F higher than the initial temperature.

Considered from another perspective, these plots show the radial temperature distribution in the polyurea under a cavitating jet. A bell shape is seen with a maximum on the jet axis and a radial decay to the ambient pressure. As the jet translation speed increases, the shift between the position of the heat source center and the measured peak temperature in the polyurea increases as expected due to the time response of the polyurea to the heat input. This shift in the position of the maximum can be linked to the jet translation speed, as shown in Fig. 25.

As the translation speed increases, the spacing between jet axis and maximum temperature increase, indicating an approximate constant time shift of ~ 4.7 s for polyurea P1000 (since the plot Δr versus the translation speed, V_t, shows the dependency Δr ~ 4.7V_t) and ~ 3.3 s for P650 (since the plot Δr versus V_t shows the dependency Δr ~ 3.3V_t), i.e. a faster response time for the stronger material.

The maximum temperature reached with different translation speeds is shown Fig. 26 for both polyurea P-1000 and P-650. In all cases, the thermocouple depth was 0.25 mm, the standoff between the jet and the coating surface was 1 inch and the jet pressure was 500 psi (3.5 MPa). For both polyurea compositions, the maximum temperature value was obtained with the slowest translation speed tested, i.e. 0.01 in/s. The maximum temperature decreased as the translation speed increased because of the polyurea response time to heat input described above and because the cavitating jet translating faster covers more area for a given time.

Finally, the width of the temperature radial distribution (as illustrated in Fig. 24) is analyzed and its variations with the translation speed are shown in Fig. 27 for both P-1000 and P-650. For each case, the width is measured at 50% of the peak maximum temperature. Fig. 27 shows that the peak width increases with the translation speed with the P-1000 showing a larger spread than the P-650. The peak width can be considered as a measure of the size of the heated region and is correlated with the jet diameter. Due to the delayed but almost constant response time (time delay Δt between the time the cavitation load is imposed and when the highest temperature is reached) of each of the two polyurea compositions (see Fig. 25), the affected region increases with the translation speed.

5. Correlation with erosion performance

5.1. Stationary cavitating jet erosion tests

In this section, we present cavitation erosion observations and measurements at higher jet pressures that what was used in the temperature tests, where we avoided damaging the thermocouples and tried to not modify permanently the polyurea coating during a temperature measurement test. The cavitation erosion tests reported below were conducted at a jet pressure of 800 psi on both the P-650 and P-1000 with aluminum 6061 as the substrate in the cavitation jet test loop described in Section 3.1. The water temperature was controlled within ± 1°C by adding ice to the water or heating the water. Tests
were conducted at four Polyurea temperatures: −10 °C, 5 °C, 20 °C, and 40 °C. The sample was left in the sample holder for some time until the sample temperature was the same as the water temperature before starting each test interval. Tests for Polyurea cooled to sub-freezing temperature were conducted in 5 °C water. The sample was cooled in a freezer until its temperature became below −10 °C, then the sample was placed in the sample holder as quickly as possible and the erosion test was run. An infrared thermometer was used to measure the Polyurea sample temperature, and Fig. 28 shows an example of the temperatures at each test interval where the sample was removed from the holder for observation and measurements, for the case of a Polyurea temperatures of −10 °C. The zigzag in the plot is due to the fact that the
The test is interrupted periodically to take measurements of the erosion. It was then necessary to cool the sample back to 

\[ -10^\circ \text{C} \]

before continuing the test.

The damage due to cavitation on the polyurea coating can be observed in Figs. 29 and 30 for two temperatures: 

\[ -10^\circ \text{C} \] and \[ 40^\circ \text{C} \]. The erosion patterns appear similar with more severe erosion at the higher temperature. Cavitation damage appeared after 5 s in the \[ 40^\circ \text{C} \] tests, while the erosion damage did not appear until 130 s in the \[ -10^\circ \text{C} \] tests. In both cases, the material failure shows plastic flow with the polyurea not being removed but instead sheared and extruded around the crater illustrating heating of the polyurea and a deep crater was formed.

Fig. 31 compares the progress of the erosion damage on polyurea P-650 and P-1000 samples for different liquid ambient temperatures for a jet pressure of 800 psi (5.5 MPa). Cavitation damage is much slower at the lower temperature and the incubation period is much longer indicating the strong effect of temperature on the properties of the polyurea and on its resistance to cavitation damage. The sample at \[ -10^\circ \text{C} \] resisted the cavitation erosion better than the sample at \[ 5^\circ \text{C} \] where the water temperature is \[ 5^\circ \text{C} \] for both. Also, the P-650 coating resisted cavitation better than the P-1000 reflecting the higher temperature rise during cavitation erosion measured on the P-1000 polyurea (see Fig. 23).

### 5.2. Translating jet erosion tests

In this section, some results of translating cavitating jets erosion tests with the polyurea P-650 and polyurea P-1000 are presented. The nozzle diameter used for these tests was 0.040 in. and the standoff between the nozzle and the sample was set to 0.55 in. Translation speeds applied to the nozzle varied from 0.01 in/s to 0.42 in/s and cavitating jet pressures from 700 psi to 1600 psi (4.8–10.3 MPa).

In Fig. 34, the failure pressures versus translation speed are compared for the P-1000 and P-650 polyurea coatings after the cavitating jet was translated across the sample. The pressure range of each run (the pressure increased automatically from left to right starting at the left edge of the sample as the jet translated also from left to right as described earlier) was selected in order to capture the failure pressure within the test for the particular translation speed. The test conditions corresponding to the numbers on the erosion tracks are given in Table 2. For all conditions and for both polyurea compositions, the erosion damage patterns are similar but appear at different times (locations) depending on the translation speed. At lower speeds, we observed wider damage patterns. At these speeds, there is sufficient time to heat the polyurea surface resulting in a wider and deeper crater. As the speed increased and the dwell time at a given sample location decreased, the erosion pattern becomes thinner and then disappears all together. From the position where the polyurea started to fail, the pressure corresponding to that location is deduced and is used to plot characteristic (Jet Pressure – Translation Speed) failure plots for the particular material. These charts characterize the interaction between cavitation and the particular coating under a wide range of cavitation intensities.

In Fig. 34, the failure pressures versus translation speed are compared between the polyurea P-1000 and P-650 samples. For a given translation speed, the pressure needed to start eroding the polyurea P-650 is higher than that needed for polyurea P-1000. This is consistent with the fact that P-650 is more resistant than P-1000 as shown in the stationary jet tests and heats up much less under the cavitating jet as seen in the previous sections. Fig. 35 shows the maximum temperature versus pressure for the two samples. The polyurea P-1000 sample shows a significantly higher temperature rise than P-650. The temperature rise and the material failure correlate well, and this can be explained by the fact that the polyurea becomes softer when the temperature is higher.

### 6. Conclusions

In this work, temperature rise in three compositions of polyurea exposed to stationary and translating cavitation jet tests have been investigated. The following conclusions were drawn:

- The temperature in the polyurea coating increases significantly as a result of its exposure to the effects of cavitation, and this temperature rise increases with the jet pressure.
• Under a circular cavitating jet, the highest temperature is right below the cavitating jet on its axis.
• The temperature in the polyurea coating is sensitive to the distance from the coating water interface and depends on the material of the substrate.
• With a Plexiglas substrate the hottest location in the coating is approximately in the middle of the coating thickness, while for an aluminum substrate the highest temperature is closer to the water-polyurea interface.
• The material of the substrate has a substantial impact on the temperature rise and on the response time, with the temperature rise with the Plexiglas substrate much higher than with the Aluminum substrate.
• A thinner coating is more resistant to cavitation erosion.
• There is a strong correlation between the temperature rise and material failure with the material being more resistant to cavitation erosion when the temperature rise is smaller.
• For all stationary and translating jet tests conducted in this study, the failure of the polyurea coating following exposure to cavitation was due to cavitation heat generation and heat accumulation in the polyurea material.

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Declaration of novelty

This contribution present original and innovative data on cavitation erosion of polyurea coatings.

• A new translating cavitating jet erosion test method is presented.
• The erosion due to a stationary and translating cavitating jet is observed and studied for a set of jet pressures and translation speeds
• Heating of the polyurea due to the cavitating jet is measured and correlated to cavitation intensity
• The strong effects of the substrate on the erosion and heating behavior is measured.

References