Experimental and Numerical Study of Polyurea Failure under Cavitation

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ABSTRACT
Observation of polyurea failure in a cavitation field suggests the strong occurrence of temperature rise in the material in addition to mechanical load. In the present work, the thermal response of polyurea under cavitation loads is studied both experimentally and numerically. In the experimental study, the temperature in a polyurea coating is monitored during exposure to a cavitating jet. Significant temperature rise in the material is clearly measured and is seen to directly increase with the cavitating jet velocity and to depend on the thickness of the coating and on the substrate material. Measurements of the material deformation and failure are seen to correlate very well with the temperature rise in the material. Numerically, the response of a viscoelastic material to the pressure generated by a bubble collapse is examined using a finite element method. Heat generation in the material is predicted from the energy dissipated by the plastic work in the material, and heat conduction is then estimated and found to have a time scale much longer than heat generation. The numerical modeling explains well the observed temperature evolution including the effects of coating thickness and substrate material.

Keywords
Cavitation, Erosion, Polyurea, Thermal Failure, Heat Conduction.

1 INTRODUCTION
Polymeric materials are becoming more widely used as coatings on ship hulls and propellers for purposes such as anti-fouling and drag reduction (Korkut & Atlar 2009; U.S. Navy 2012). With increased applications of these coating materials on propellers and rudders, it is necessary to investigate their resistance to cavitation. Among various polymeric materials, polyurea has been presented by its proponents as being of particular interest due to its easy application and good performance against shock from explosions (Amirkhizi et al 2006). In recent years, we have conducted extensive cavitation erosion tests on various polymeric and other coatings and observed different modes of failure with polyurea showing a combined mechanical and ‘thermal’ failure (Choi & Chahine 2015). This is explained by the fact that repeated cavitation bubble collapses on the polyurea impart repeated stresses resulting in cycles of deformation and viscous and plastic work, which generate heat in the material. Since polyurea is a poor heat conductor, the generated heat accumulates to different extents depending on the thickness of the coating and on the heat conduction properties of the substrate. The shear modulus of polyurea is very sensitive to temperature, and the material becomes softer as the temperature increases. In the end, the material cannot withstand the stress and starts to flow like a molten material as shown in Figure 1.

In this paper, the thermal response of polyurea to cavitation loads is studied both experimentally, using the cavitation generated by cavitating jets, and numerically, using a structural finite element method code. The temperature in the polyurea is monitored over time for different cavitating jet pressures and different polyurea coating thicknesses and different substrate materials.

2 EXPERIMENTAL STUDY
2.1 Polyurea Sample Preparation
A circular polyurea sample molded in a 6 mm thick Plexiglas holder and equipped with a PVDF transducer, as shown in Figure 2, was used for the initial tests. The PVDF pressure measurements are not reported in this paper. The diameter of the polyurea coating area was 1 inch, and the thickness of the polyurea was 2 mm. The polyurea was prepared at the University of Massachusetts at Lowell, by mixing Isonate 2143L and Versalink (Amirkhizi et al 2006).

To monitor the temperature distribution in the material, four K-type thermocouples (Omega® Model No. 5SC-KK-K30-36) were implanted at 2.5 mm intervals, with the first thermocouple positioned at the jet axis. The 0.25 mm diameter thin thermocouples were installed from the bottom of the sample through holes made in the substrate. After inserting the thermocouples, the hole was sealed with silicon adhesive E6800 to prevent the sensitive tip of the thermocouple from being exposed to the
surrounding water. A Thermocouple-to-Analog Converter (Omega®, SMC-J) was used. In following tests, the depth of the thermocouple was also varied to monitor temperature at different depths.

2.2 Test Setup

The cavitation jet erosion test facility used in this study is a DYNAFLOW flow loop commonly used for controlled cavitation erosion testing of materials. It is composed of a CAVIJET® nozzle with a 0.086 inch orifice diameter, a sample holder, a test tank, a water reservoir, and a pump capable of generating up to 1,200 psi at a flow rate of 5 gpm (Chahine et al 2014a). The cavitation is generated at a sharp corner in the exit orifice and induces 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 as in hydrodynamics applications with distribution of various size micro bubbles, which collapse on the test material surface.

2.3 Temperature Measurement

The present experiments were conducted at pressures ranging from 300 psi to 500 psi. Figure 3 shows the time evolution of the temperature during the tests. The temperature of the polyurea prior to the test was equal to the water temperature in the test tank. During the first 1 minute, this initial temperature, $T_i$, was recorded. As soon as the cavitating jet was turned on, the temperature in the polyurea started to rise sharply, and then in a couple of minutes the temperature reached a maximum saturation value where 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 polyurea started cooling down quickly, and within a couple of minutes the temperature returned to the tank water ambient temperature. The final temperature was usually a couple of degrees higher than the initial temperature due to gradual warming of the water temperature in the test tank during the test.

2.4 Depth-wise Temperature Distribution

The temperature distribution in the depth direction was studied by placing the thermocouples at different depths from the polyurea-water interface and repeating the tests. Two different substrate materials, Plexiglas and Aluminum 6061, were studied since very different cavitation erosion performance was observed between these two substrate materials. The thermal diffusivity of the two materials is $1.1 \times 10^{-3}$ m$^2$/s for Plexiglas and $9.7 \times 10^{-3}$ m$^2$/s for Aluminum 6061.

Figure 4 shows the maximum (or equilibrium) temperature versus the distance from the coating surface (thermocouple depth) for four different radial distances from the jet axis ($r = 0$). The results with the Plexiglas substrate clearly show that the temperature distribution has a maximum inside the coating thickness, here at a 1 mm depth, regardless of the radial location.
The highest temperature (T), is the maximum of the ve. If the T, represents the current under the jet, the heat conducted with T+ is illustrated that the T–C–B, reflects of the T=–m. The results are shown in Figure 6 for three values of the pressure drop across the nozzle. At the highest pressure, 500 psi, we can see that the maximum temperature rise is 14°F for the 2 mm thick polyurea, 10°F for 1 mm thickness, and 2°F for 0.5 mm thickness. The lower temperature observed in a thinner coating can be explained by the heat conduction in the polyurea and dissipation in the substrate. If the thickness is smaller, heat dissipates quicker through a shorter distance to the substrate surface. Since polyurea becomes weaker as the temperature rises, thinner coatings would be more resistant to cavitation erosion than thicker ones. This is consistent with our observation of the polyurea failure under cavitation (Choi & Chahine 2015).

Figure 4. Maximum temperature distribution versus the distance from the coating surface in a 2 mm thick P-650 polyurea coating on a Plexiglas substrate. The jet pressure was 500 psi and the nozzle standoff was 1 inch.

Figure 5. Maximum temperature distribution versus the distance from the coating surface at r = 0 in a 2 mm thick P-650 polyurea coating with an Aluminum substrate. The nozzle standoff distance was 1 inch.

Similar tests were conducted with an aluminum substrate. The thermocouple depth was varied at a fixed radial location r = 0 (under the jet center). The maximum temperature as a function of thermocouple depth is shown in Figure 5. Notice that the highest temperature rise is 19°F with the aluminum substrate at 500 psi, whereas the highest temperature rise with the Plexiglas substrate was 63°F at the same pressure. The polyurea coating on the aluminum substrate showed a monotonic temperature distribution with the highest temperature measured near the polyurea-water interface. This illustrates that the material of the substrate has a strong influence on the heating and on the temperature distribution in the coating.

2.5 Effect of the Coating Thickness

Figure 6 shows the effect of the polyurea coating thickness on the temperature rise under the influence of cavitation. Three different thicknesses of the polyurea coating on an aluminum substrate were tested, and the temperature rise was measured at the mid-thickness depth. The results are shown in Figure 6 for three values of the pressure drop across the nozzle. At the highest pressure, 500 psi, we can see that the maximum temperature rise is 14°F for the 2 mm thick polyurea, 10°F for 1 mm thickness, and 2°F for 0.5 mm thickness. The lower temperature observed in a thinner coating can be explained by the heat conduction in the polyurea and dissipation in the substrate. If the thickness is smaller, heat dissipates quicker through a shorter distance to the substrate surface. Since polyurea becomes weaker as the temperature rises, thinner coatings would be more resistant to cavitation erosion than thicker ones. This is consistent with our observation of the polyurea failure under cavitation (Choi & Chahine 2015).

Figure 6. Maximum temperature at mid-thickness versus pressure for three thicknesses (0.5, 1.0, and 2.0 mm) P-1000 polyurea on aluminum substrate. Nozzle standoff was 1 inch.

3 NUMERICAL MODELING AND ANALYSIS

3.1 Material Model

In this study, DYNA3D, a Finite Element Method (FEM) code developed at Lawrence Livermore National Laboratory (Whirley & Engelmann 1993) was used to model the response under cavitation loads. The Johnson-Cook material model (Johnson & Cook 1983) was selected because the model allows modeling plastic deformation of the material and strain rate effects, and can output the temperature distribution in the material. The model describes the stress-strain relation by the following phenomenological equation:

$$\sigma = (A + B\dot{\varepsilon}^n)(1 + C\dot{\varepsilon}^m)(1 - (T/T_0)^n),$$  \hspace{1cm} (1)

where the normalized strain rate, \(\dot{\varepsilon}^* = \dot{\varepsilon}/(1 s)^{-1}\), is the strain rate relative to \(1 s^{-1}\), and the normalized temperature, \(T^* = (T - T_0)/(T_m - T_0)\), represents the current temperature, \(T\), in relation to the reference temperature, \(T_0\), and the melting temperature, \(T_m\) of the material.

Split Hopkinson Pressure Bar tests were conducted to obtain the material parameters of polyurea as described in Choi & Chahine (2015). A series of tests were conducted at various strain rates up to 12,000 s\(^{-1}\). The stress-strain relations were then obtained and curve-fitted with these parameters: \(A = 0.43\) MPa, \(B = 0.14\) MPa, \(n = 0.613\), and
3.2 Synthetic Cavitation Loading

In order to study the effects of the magnitude of the impulsive cavitation loads parametrically, synthetic loading was considered in this paper as in (Choi et al 2014). Previous numerical and experimental studies (Jayaprakash et al 2012, Singh et al 2013, Chahine et al 2014b) indicate that the pressure peaks in the cavitation fields can be properly represented with a Gaussian function in space and time. Thus, in this work, an idealized time and space varying impact pressure loading, \( P(r,t) \), is considered and has the following expression:

\[
P(r,t) = P_0 e^{-\left(\frac{r}{\Delta r}\right)^2} e^{-\left(\frac{t}{\Delta t}\right)^2},
\]

where \( P_0 \) is the amplitude of the pressure pulse, \( \Delta r \) is the characteristic loading duration, and \( \Delta t \) is the characteristic radius of the loading footprint.

3.3 Polyurea Behavior under Successive Impacts

Repeated synthetic cavitation impulsive loads field are investigated in this section. Six bubble collapses are considered for illustration, each having a magnitude of 20 MPa, a duration \( \Delta t = 1 \mu s \), and a radial extent of \( \Delta r = 100 \mu m \). The first pressure peak occurs at 3 \( \mu s \), and the intervals between successive peaks are 4 \( \mu s \).

Figure 8 shows temperature rise contours in a vertical cross section inside the polyurea coating at four different times. From left to right, the first plot shows the temperature distribution at the time the temperature reaches a maximum following the first impact; the second plot shows the temperature contours at the time the temperature reaches a minimum between the first and the second pressure peaks.

The third and fourth plots show the temperature distribution at the maximum and minimum temperature achieved after the second impact and before the third impact.

3.4 Thermal Balance Equation

The thermal balance equation in the material can be written as:

\[
\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x_i^2} + \beta \sigma_{ij} \dot{e}_{ij}^p - \alpha E T \dot{e}_{ii}^b, \quad (3)
\]

where \( \rho \) is the density of the material, \( c_v \) the specific heat, \( T \) the temperature, \( t \) the time, and \( k \) is the thermal conductivity, \( \beta \) is a coefficient that represents the portion of strain work converted to heat energy, \( \alpha \) is the thermal expansion coefficient, \( \sigma_{ij} \) is the stress tensor, \( \dot{e}_{ij} \) is the strain rate tensor, and \( E \) is the Young’s modulus (Ravichandran et al 2002).

The left-hand side of Eqn. (3) is the rate of change of the thermal energy due to temperature variation, while the first term on the right-hand side is the thermal energy dissipation due to conduction. The second term on the right-hand side is the plastic strain work converted into thermal energy, and the last term is thermo-elastic heating due to the material compression or expansion in the elastic range. For the polyurea, these material properties are known: \( \rho c_v = 1.977 \times 10^{-3} \text{ J/(mm}^2 \text{K)} \), \( k = 0.2 \text{ W/(m K)} \), \( \beta = 0.9 \), \( \alpha = 7 \times 10^{-6} / \text{K} \), and \( E = 15 \times 10^6 \text{ Pa} \).

For the present cavitation erosion study, large plastic deformations occur, and we can neglect the smaller thermo-elastic heating term and rewrite Eqn. (3) as:

\[
\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x_i^2} + S, \quad (4)
\]

where \( k/(\rho c_v) \) is the thermal diffusivity. The plastic strain work term,

\[
S = \frac{\beta}{\rho c_v} \sigma_{ij} \dot{e}_{ij}^p, \quad (5)
\]

is treated as a source term to solve Eqn. (4) numerically. Since the heat conduction equation is numerically stable, a central difference is used to discretize it in Cartesian coordinates. The temperature is defined at the cell center while the coordinates are defined at the nodes. This discretization is also consistent with DYNAN output. For
time integration, the first order Euler method is used. In the present study, the material FEM dynamics and the heat equation are coupled in one-way, i.e. the material dynamics solution is fed to the heat equation through the source term in Eqn. (5). However, the temperature change on the material properties is not considered yet. In the future, we will consider an iterative approach going back and forth between the FEM and thermal solutions to better simulate material failure. Here we address material response prior to the failure.

The boundary conditions are illustrated in Figure 9. One quarter of the polyurea domain is modeled, and a zero temperature gradient condition is applied on the two symmetry planes at $x = 0$ and $y = 0$. At the material-water interface, $z = 0$, the temperature is equal to the temperature of the water which is assumed constant, $T_{\text{water}}$, during the simulation. At the bottom edge of the material (i.e. on the substrate interface), the temperature is set to a constant temperature, $T_\infty$.

Figure 9. Boundary conditions for the heating and conduction problem in a polyurea coating.

3.7 Temperature with Conduction

Using the above formulation, conduction and heat generation in the polyurea were calculated as a result of six consecutive 20 MPa impulsive pressures applied at the origin (0,0,0).

Figure 10 shows the final temperature distribution in the polyurea, which is not much different from the final temperature distribution without including the heat conduction. In order to show the difference of the two cases, the final temperature distribution without the conduction is subtracted from the distribution shown in Figure 10. That is, $T_{\text{conduction}} - T_{\text{no-conduction}}$ is shown in Figure 11. The temperature difference is very small, but we can observe that the hottest spot (60 µm below the impact) is slightly cooler when the conduction is considered.

Figure 11. Contour plot of the excess temperature due to the inclusion of heat conduction in polyurea following six consecutive synthetic cavitation loads of magnitude 20 MPa.

Figure 12 compares the temperature time history at three depths along the axis of symmetry under the impact loads. Near the 60 µm depth, the first impact increases the temperature the most (about 50% of the total temperature rise), and the contribution of the following impacts to the temperature decreases as the loading cycles continue (about 50% of the temperature rise for all five loads). The effect of conduction is again negligible. This is due to the very short time of the loading relative to the conduction characteristic time. During the 28 µs, heat did not propagate much through the polyurea.

Figure 12. Comparison of the temperature time histories at three locations following six consecutive synthetic cavitation loadings of magnitude 20 MPa, $\Delta t = 1$ µs, and $\Delta x = 100$ µm. The results with and without conduction are indistinguishable.
3.8 Late Time Conduction after an Impact

In this section, heat conduction in polyurea for relatively long time durations is considered. The temperature distribution after one 20 MPa impact is taken as the initial temperature distribution, and heat conduction for the following 10 ms is simulated.

The substrate is modeled as another material with a thickness of 4.8 mm. Aluminum with a thermal diffusivity, \( k/(\rho c) = 9.7 \times 10^{-5} \text{ m}^2/\text{s} \), is considered. Note that the thermal diffusivity in the 0.2 mm thick polyurea coating, \( 1.01 \times 10^{-7} \text{m}^2/\text{s} \), is three orders of magnitude smaller.

Figure 13 shows the final temperature distribution after 10 ms. We can observe that the temperatures in the depths \( z \leq 4.8 \text{ mm} \) are slightly lower than the earlier case without the substrate. However the temperature near the hottest spot is similar to that of the case without the substrate.

![Figure 13. Temperature distribution in a 0.2 mm thick polyurea with a 4.8 mm thick aluminum substrate 10 ms after a synthetic cavitation loading of magnitude 20 MPa is applied.](image1)

In the next simulation, the time interval between two impacts is reduced to 10 µs, and the resulting temperature changes due to conduction after a synthetic cavitation loading of magnitude 20 MPa.

Figure 14 compares at three depths the two cases: a 5 mm polyurea without a substrate and a 0.2 mm thick polyurea over a 4.8 mm aluminum substrate. The temperature at the hot spot at the 60 µm depth decreases with time and eventually the temperatures at 60 µm and 120 µm become the same. The surface also cools down over time. The temperature histories of the two cases are almost on top of each other. This is due to the slow conduction in the polyurea and the relatively short time considered. The substrate boundary at \( z = 200 \mu \text{m} \) is still too far to observe the effect of the substrate within this simulation time of 10 ms.

3.9 Multiple Impacts with Conduction

In this section, we conduct simulations for much longer time duration with multiple impacts.

The first simulation is for a 5 mm thick polyurea with no substrate. Figure 15 shows the temperature vs. time at the three depth locations for 20 impulsive loads with the interval between two impacts being 0.1 s. Thus the total simulation time is 2 s. After three impacts, the temperature variations reach a repeating pattern. In this case, the heat does not accumulate because the time intervals between the impacts are long and the temperature drops down to almost the initial temperature before the next impact arrives.

![Figure 15. Temperature in the 5 mm thick polyurea subjected to a repeated synthetic cavitation loading of magnitude 20 MPa with 100 µs intervals. No substrate is modeled in this simulation.](image2)

In the next simulation, the time interval between two impacts is reduced to 10 µs, and the resulting time history is shown in Figure 16. Now the heat generating event is more frequent compared to the time needed for cooling by conduction. As a result, the heat accumulates and temperature rises over time. One interesting observation in the first two cycles is that the hottest spot moves from the initial 60 µm depth to a depth of 120 µm two cycles later. This is due to heat conduction into the deeper portion of the polyurea and active cooling at the coating surface by the water.

Next, a simulation with an aluminum substrate is shown. Figure 17 plots the temperature distribution in the polyurea (top 0.2 mm) and in the aluminum (\( z \leq 4.8 \text{ mm} \)) when the 20 MPa load is repeated at 10 µs intervals. The left figure shows the temperature distribution after the first impact, and the right figure shows the final temperature distribution after 20 impacts. The figures show how the thermal energy propagates into the aluminum substrate as it is building up due to repeated heat addition. Figure 18 compares the time histories of temperature at three depths. During the first
few loading cycles, there is no difference between the two. However, as the heat accumulates, higher temperatures develop, and conduction starts to show its effects. This is most visible at the 120 µm depth because this location is closest to the relatively colder aluminum boundary.

Figure 16. Temperature in a 5 mm thick polyurea subjected to repeated synthetic cavitation loading of magnitude 20 MPa with 10 µs intervals. No substrate is modeled in this simulation.

Figure 17. Temperature distribution right after the first impact (left) and at t = 0.2 s for a 0.2 mm thick polyurea on aluminum substrate subjected to repeated synthetic cavitation loading of magnitude 20 MPa with 10 µs intervals. The aluminum substrate (z ≤ 4.8 mm) is modeled as a conducting material.

Finally, a similar computation is shown with the assumption of constant temperature in the substrate. Figure 19 shows the temperature distributions after the first impact and after the last 20th impact. Figure 20 compares the temperature time histories between this case and the case where the whole 5 mm thickness is made of polyurea. Due to the assumption of a constant temperature substrate, the temperature rise reached a balanced temperature cycle of around 3°C, which is lower than the 4.5°C value obtained with the fully modeled substrate (Figure 18). However, the overall trend of the temperature behavior is similar between the two models of the substrate.

Thermal simulation of polyurea with multiple impacts with proper time intervals shows that the effect of heat conduction is measureable over long time even though the heat conduction during an impact time scale of 1 µs is negligible. As the temperature rises, the thermal weakening of material (not included here) can be considered by...
running a new material simulation with the material properties of polyurea at the elevated temperature as shown in Figure 7.

4 CONCLUSIONS

Temperature measurements in polyurea subjected to cavitation from a cavitation jet show that the temperature in the polyurea coating increases over time until reaching an equilibrium temperature. The temperature rise due to cavitation is seen to increase with the intensity of cavitation or with the jet pressure. This temperature increase varies with the location inside the polyurea coating. For a polyurea coating over a Plexiglas substrate the hottest spot is measured to be half-way into the coating thickness, while for polyurea coating on an aluminum substrate the highest temperature is closer to the surface of the coating. The temperature rise is higher for thicker coatings. These trends of measured temperature behavior are consistent with the observations of polyurea failure under cavitation. In general, thinner coatings are more resistant to cavitation erosion, and the substrate material has a substantial impact on the temperature. There is also a strong correlation between the temperature rise and material failure.

In the numerical study, the heat generation by cavitation bubble loading was modeled by synthetic loading and a finite element method model of the polyurea coating using the Johnson-Cook material model. Plastic work in the polyurea was then converted into the heat generation, and heat conduction was taken into account. Large difference in the time scales of heat generation and heat conduction justify decoupling heat generation and conduction calculations. The simulations show that conduction in the polyurea during one or several collapses of a few milliseconds is not important due to the short time relative to the characteristic time of conduction in the material. However, heat accumulation due to repeated impacts and heat conduction over longer times of the order of seconds is quite important.

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REFERENCES


DISCUSSION

Question from Sören Schenke

What is the most important flow characteristic to determine the frequency of temperature loading?
Author’s closure
The data presented in this paper shows that the frequency of thermal loading is the same as the frequency of occurrence of cavitation impulsive pressures which are strong enough to result in large stress and deformation in the material. In terms of flow characteristics, this involves the number of bubble nuclei in the water, the local low pressures that initiate bubble growth, the flow velocity in the low pressure region, and the relatively high ambient pressure that drives the bubble collapses. The frequency of loading would increase if there are more nuclei per unit volume of water, and larger nuclei would cavitate more easily even with moderately low local pressures. For a given nuclei size distribution, a lower local pressure will drive more nuclei to grow into cavitation bubbles. A slower flow would provide the nuclei with a longer residence time in the low pressure region and would increase the number of cavitation bubbles. A higher local pressure in the bubble collapse region would result in stronger collapses. All these factors combine to determine the frequency of the loads that are strong enough to generate heat.

Questions from Yin Lu Young
How important do you think is the curling stress effect due to the limited extent of the circular disk? How about the influence of potential debonding between the polyurea and aluminum?

Author’s closure
The 25 mm diameter polyurea disk is 2 mm thick and is surrounded by Plexiglas. The molding process involves mixing of two chemicals at room temperature and curing the polyurea under a uniform temperature. Therefore, curling stress due to temperature gradient in the material is minimal.

Concerning the far field boundary in the numerical simulations, its effect is negligible because the radius of the loading is 100 µm while the radius of the far field boundary is 50 mm, i.e. 500 loading radii away. However, the bottom boundary is much closer, at 2 mm, and its effects are properly taken into account in the numerical study. In the structure, we could observe the stress-strain waves from the impact propagate through the thickness and reflect back from the bottom boundary, which was assumed rigid.

In practical applications, the bonding between the coating and the substrate is very important. Through many cavitation erosion experiments conducted at DYNAFLOW, we have often seen premature failure due to the delamination of the coating. However, we did not experience any debonding issues during the experiments described in this paper since a special pretreatment procedure was applied at the aluminum surface and provided strong bonding between the polyurea and the aluminum.