POOL FIRE EXTINCTION BY REMOTELY CONTROLLED APPLICATION OF LIQUID NITROGEN

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ABSTRACT

This manuscript being an extension of previous work on extinction by liquid nitrogen presents a technique for effective remotely-controlled application of the cryogen to fires. The cryogen is carried to an event in insulated and vented containers in trucks; there from it is pumped to the fire through a vacuum-insulated hose, fitted with cryogenic valves. Application of the cryogen from a distance, by spraying through a nozzle, proved challenging, as the ensuing liquid ligaments rapidly vaporize along their trajectory paths. To the contrary, use of a remotely-guided unmanned robotic vehicle to carry the hose to the fire and discharge the cryogen therein much more effective. Upon contact with a pyrolyzing/burning surface, abrupt vaporization of the cryogen generated cold vapors, which spread by gravity and blanketed the burning area. The pyrolyzing gases were inerted, the surface cooled and its pyrolysis rate reduced, air separated from the fuel and, hence, the fire extinguished. To demonstrate this technique, experiments were conducted with pool fires of isopropanol. A small robotic vehicle was designed and constructed in-house to deliver small quantities of the cryogen extinguished to small-scale pool fires, arranged in different patterns. Fire extinction in these feasibility tests was fast and effective.

KEYWORDS: fire extinguishing, pool fires, liquid nitrogen, suppression, cryogen application.

INTRODUCTION

This study was conducted to assess practical methods of delivery of liquid nitrogen (LN_2) to fires. In previous research [1-5], direct application of liquid nitrogen was shown to effectively extinguish pool fires of various fuels, such as ethanol, isopropanol and Diesel oil. It was determined that cryogen quantities of one litter were sufficient to extinguish one square meter fires. The cryogen was carried in open containers, and it was manually poured at the edge of these fires. However, as heat fluxes from large fires render their approach by fire-fighting personnel perilous, methods for delivery of the cryogen from a safe distance were explored in this work. Transportation of the cryogen in vented container trucks and delivery to the periphery of the fire by specially-insulated hoses is a given, as the technology exists, but its application therefrom is the subject of this work. Taking into consideration approximately safe distances from the fire, application of the cryogen by fire-fighting personnel was examined using the traditional hoze/nozzle approach. Results are presented herein. However, as the evaporation of the cryogen in an open atmosphere proved to be exceedingly fast for effective operation, delivery by remotely-controlled unmanned vehicles was examined next. Feasibility results on this technique are subsequently presented.

Liquid nitrogen is a rather environmentally-benign extinguishing agent that does not cause property damage, groundwater contamination or atmospheric pollution. However, as it displaces oxygen, it is an asphyxiating agent. Hence, care should be exercised in it transportation, handling and application.

APPROACH

i) Cryogenic Equipment

Liquid nitrogen can be carried to the site in commercially available trucks, equipped with cryogenic pumps and well-insulated hoses, see Fig. 1.

Figure 1. Photographs of (a) a commercial liquid nitrogen truck, (b) cryogenic pump and (c) hose.

The cryogen-carrying truck should not be allowed to come close to the fire, as excessive heat fluxe therefrom may cause rapid liquid nitrogen vaporization and pressure build-up in the tank. Comprehensive experimentation should be conducted to determine safe distances from large fires, such as a Jet-A/Kerosene airport tarmac fire. Herein an estimation of the distance of the truck from the fire is made on published parameters. This is only a feasibility study meant to examine the magnitude of the heat loss in a hose, it is not meant to provide recommendations on safe distances. Guidance to this inquiry may be provided by the work of Nolan [6] in conjunction to the work of Koseki [7]. Nolan reported the following threshold heat fluxes: (i) 37.8 kW/m^2 was identified as the level of radiative heat flux upon which major damage can be caused to a process plant and storage tank equipment; (ii) 12.6 kW/m^2 was identified as the level of radiative heat-flux where secondary fires may start to occur; (iii) 4.7 kW/m^2 was identified as the heat flux that can cause pain on exposed skin. These threshold radiation fluxes are encountered at various distances from the center of the fire pool. The radiation flux obeys the inverse-square law. This law applies when energy is radiated outward radially from a point source. Hence, the radiation passing through any spherical unit area is inversely proportional to the square of the distance from the point source.

$$Q_{\text{flux}} = Q_0 / (4\pi R_o^2)$$
(1)

Where Q_{flux} is the radiation flux at a distance from the point source, Q_0 is the energy of the point source, R_o is the distance from the point source. Of course, the fire is a distributed source of radiation, not a point source, but the inverse square law is still valid at distances away from the fire.

Koseki [7] measured heat fluxes from large kerosene pool fires, up to 50 meters in diameter. His data showed that at a distance of $L/D = 5$ from the center of such fires (where L is the distance to the center of the fire and D is the diameter of the fire), the highest heat flux value for a 3 m, in diameter gasoline fire was 1.9 kW/m^2. Koseki explained that this normalized maximum heat flux of 1.9 kW/m^2 occurs with pool fires with a diameter of 3 meters and then decreases as the pool fire grows larger due to the effects of soot interference from bigger diameter fires. Indeed, he measured only 0.23 kW/m^2 in the case of 50 m, in diameter, kerosene fires. The height of the former flame was reported to be nearly two times the diameter, i.e., approx. 6 m; no value was reported for the latter flame. The data represent the heat flux recorded after the fire was allowed to develop fully. In other words, they represent the maximum heat flux of the fire event. Thus, since the flux of 1.9 kW/m^2 is well below all three threshold values reported by Nolan [2], this value is used herein to estimate an order of magnitude for the distance between the truck the fire. To proceed with this calculation, a 100 m^2 pool fire was assumed and was approximated as a steady-state circular pool fire with a diameter of 11.3 meters. If this maximum value for heat flux (1.9 kW/m^2) at a distance of $L/D = 5$ is used, as reported by Koseki, then the minimum distance of the truck from the center of the pool fire can be calculated as : $L = 5 \text{ x } 11.3 = 56.5$ meters. This calculation is used to estimate the length of the hose that would be needed to reach the fire; it is calculated to be the order of 50-100 meters. However, the safety of such distances has to be proven experimentally. Moreover, the reader should be aware of the fact that the size of the fire may vary during any given event, and it is not known a priori.

The hose chosen for scaled-down testing herein was a *Semiflex* vacuum-jacketed hose from *Vacuum Barrier Corporation (VBC)* with a 2.54 cm inner diameter and a length of 10 meters, shown in Fig. 1. This hose is specifically designed for cryogenic applications. The hose is also flexible and has a protective outer shell for use in hazardous environments. With an advertised heat loss rating of only 1W/m (1BTU/ft/hr), this hose makes for an ideal mass transfer component between the supply tank and the location where the liquid needs to be applied. This value was confirmed by independent calculations, see Appendix 1. The total heat loss flux for a 50 m hose would then be 50 W. As the latent heat of vaporization of LN_2

is approx. 200 kJ/kg, and if a flowrate of 0.5 kg/s is assumed, the heat flux needed for vaporization is 100 kW. A heat transfer analysis of the hose showed that upon achieving steady state-conditions, after an initial transient cool-down period, the LN_2 flow remains liquid through the end of the hose, with temperatures near the 77K boiling point of nitrogen.

ii) Fire Extinction Experiments with a Hose-Valve-Nozzle Equipment

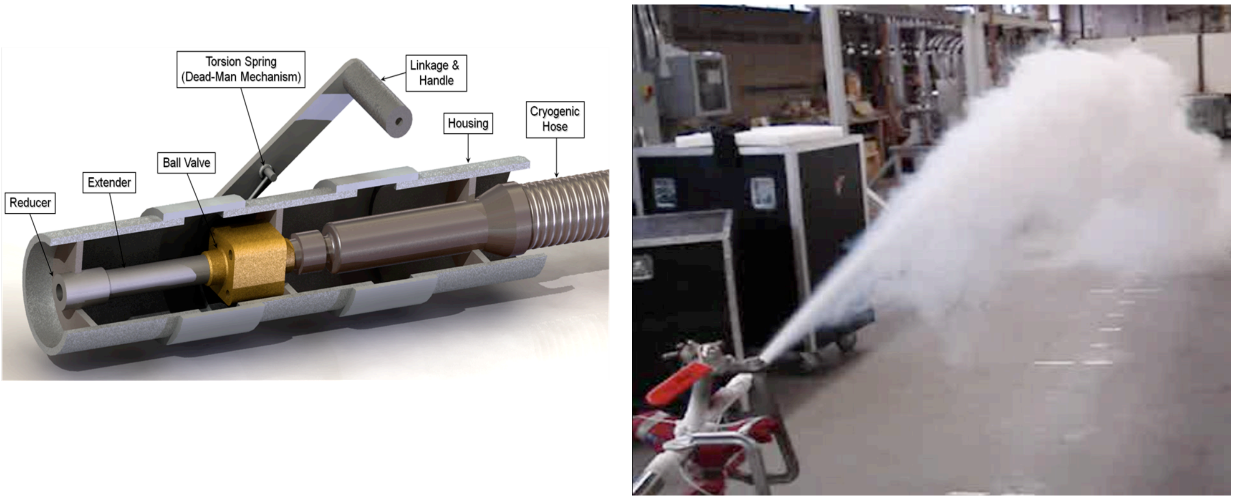

Figure 2. On the left: schematic of the experimental equipment encompassing the cryogenic hose, the ball valve and the reducer nozzle in a casing. On the right: liquid nitrogen jet trajectory under pressure.

Tests were conducted in an open room (at STP) with the apparatus depicted in Fig. 2. The goal was to determine the quality and length of the liquid nitrogen jet. The apparatus consisted a 10 meter long *Semiflex* vacuum-jacketed hose from *Vacuum Barrier Corporation (VBC)* with a 2.54 cm (1″) inner diameter, a 1 cm cryogenic ball valve and a stainless steel nozzle (either 1.1 or 1.9 cm in diameter). Upon an initial cool down period of approximately 3 minutes, the system reached steady-state operating temperature, as monitored by thermocouple attached at the end of the nozzle assembly. Various LN_2 supply pressures were used in this test, in the range of 20-414 kPa (0.2-4.14 atm). Results showed that given the rather small diameters of the hose, valve and nozzles used herein (all $\leq$ 2.54 cm), higher pressures did not help in delivering liquid to a target as they enhanced the evaporation of the cryogen in flight. The most liquid was found at lower pressures, but at these conditions the jet only traveled short distances. Intermediate pressures of 138-414 kPa in increments of 69 kPa were tested and the pressure of 345 kPa provided the best balance between distance travelled and liquid quantity at the target. This combination successfully delivered liquid nitrogen to just less than 10 meters, using the nozzle of 1.9 cm.

A fire extinction test was then performed targeting two small alcohol fires, set at distances of approximately 5 and 7 meters away from the nozzle. The system was able to successfully extinguish the former fire, but took quite a while to do so. Liquid reached the latter, but not in quantities sufficient to extinguish it. Figure 3 shows elapsed-time photos from the start of LN_2 flow to the extinction of the fire.

Figure 3. Photographs of fire extinction of a small alcohol-fueled fire, set at a distance of 5 meters away from the LN_2 nozzle. (**i**) Time: 0s, LN_2 valve is opened. (**ii**) Time: 7s, small quantities of liquid LN_2 reach the fire. (**iii**) Time: 36s, increasing quantities of liquid LN_2 reach the fire. (**iv**) Time: 90s, the fire is extinguished.

These tests did show some promise. Liquid cryogen was delivered to the end of a hose-nozzle system and that liquid was sent a distance through the air, landing on and extinguishing a pool fire. However, shooting a large quantity of liquid and gas towards the fire did not prove to be as effective as pouring the LN_2 directly on the fuel [1]. In a jet, LN_2 liquid is transported as ligaments/droplets and the large surface area of the multitude of LN_2 droplets in the spray enhances in-flight vaporization. Only a fraction of the liquid nitrogen that leaves the nozzle reaches the fire. High supply pressures and small nozzle orifices increase the reach of the jet, but caused significant increases in cryogen. The optimum nozzle orifice and supply pressure requires a balance between maximum distance and maximum percentage of liquid at the target location. It was determined that the greater the fluid exit velocity, the greater the travel distance possible, but the smaller the liquid to vapor ratio. The best way to overcome this hurdle is to use the largest hose, valve, and nozzle assembly available. Finally, tests were performed with varying jet angles, between 5 and 15 degrees from the horizontal. It was determined that at larger angles, the amount of liquid reaching the fire decreased, as the lengthier trajectory through the air enhanced boil-off.

iii) Remotely-Controlled Fire Extinction Experiments

Learning form the above experiences, it was decided to use a remote controlled vehicle to discharge the LN_2 close to a fire, see Fig. 4. The advantages of this concept would be that existing robot chassis are available (see I-Robot [8,9], FFR-1 from InRob Tech [9], they can be operated from a safe remote location, they are well-insulated so that they can be positioned at the edge of the fire. The LN_2 would be supplied remotely through a hose and discharged as a free stream, flowing through an insulated boom mounted on a rotary turret. The disadvantages would be that the system would require a robot, supply truck, operators, as well as an umbilical cord that will contain the hose and the power cable. Whereas a battery pack may be installed in the vehicle, it is an was thought better to power the vehicle remotely to avoid carrying the extra load of heavy batteries.

The Maximum exposure temperature that the robotic vehicle and the boom would be exposed to temperatures in the order of 1000 °C, and the maximum exposed heat flux would be 50 kW/s. Necessary LN_2 flowrates may be estimated based on past large scale tests by the FAA [10, 11], back when a substitute for Halon 1211 was being sought. They tested Halon, Halotron I and C6F14 and determined that flowrates in the order of 1-1.5 l/s were adequate to expediently extinguish airport tarmac fires. Whereas the mode of fire extinction of LN_2 is not the same as that of the chemical extinguishers, the required flow rates are not expected to be too different. Levendis and Delichatsios [1] used a flow rate in the order of 0.25 l/s to extinguish a 1 m^2 fire.

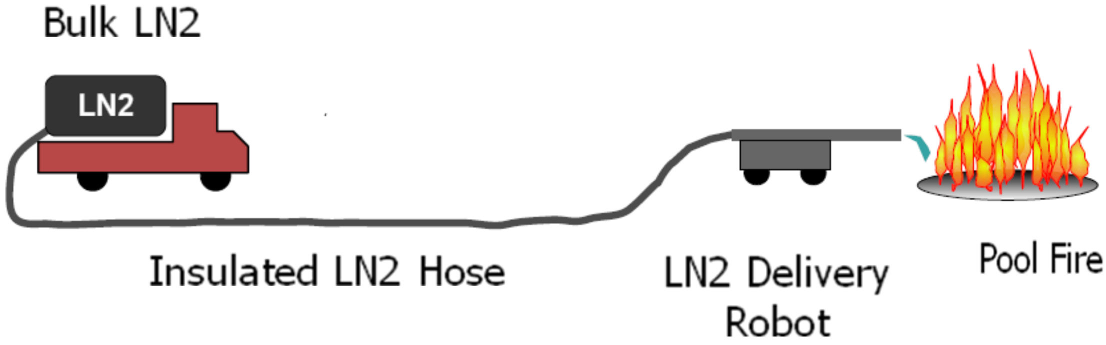

Figure 4. Schematic of a remotely-controlled vehicle used to discharge the LN2 close to a fire.

To test the effectiveness of remote-controlled application of LN_2 to a fire, a small-scale robotic vehicle was constructed in-house. The main goal for this prototype was to show that the robot could move close to a fire, while dragging a hose, and effectively deliver LN_2. Moreover, it should be able to go forward, reverse, and turn left and right. This vehicle incorporated a rechargeable battery. The prototype is shown in action in Fig. 5. It is able to travel at a speed of 3.3 m/s (0.79 km/hr). Based on speed, the prototype may be designated as 1/14th scale of a commercial robot (see iRobot Corporation, Warrior platform). The prototype is capable of over 80 N of pulling force and can drag a hose that weights 85% of its own weight along concrete pavement. The prototype can be sufficiently maneuverable to drive in a circle, although it can not turn and move forward at the same time. All turns are accomplished by moving one track forward and the other backward, pivoting in place. The boom turret was kept stationary in these tests.

Initial tests were conducted to assess the maneuverability of this prototype vehicle and its ability to wet a designated area. A water hose was fitted. Pivoting and advancing through the area was an optimum motion pattern, since circumnavigating the fire proved to be an issue because the umbilical cord began to interfere with the vehicle's progress.

Subsequent tests were conducted at the premises of Vacuum Barrier Corporation at Woburn, Massachusetts. The robotic vehicle was fitted with a 0.95 cm (3/8") ID cryogenic CobraFlex cryogenic hose. In addition to demonstrating the feasibility of LN2 delivery with a remote-controlled robotic vehicle, testing was also conducted to discover any issues with the human-machine interface; and to benchmark the flow rate of LN2. The tests were documented by video and still cameras. Instead of spilled jet fuel, small alcohol fires were lit in disposable aluminum pans, each having a surface area of 0.094 m^2. The pans were arranged in two different configurations and were filled with iso-propanol to a depth of approximately 1 cm. The fuel was ignited using a lighter with an extended reach. To avoid overwhelming the small fires, a cautious approach was taken. The supply gage pressure was reduced to 9 psi, by venting the tank, and the nozzle was removed from the hose to avoid spraying. A suitable flow was established, which was then measured gravimetrically to be 0.0142 L/s.

Two different arrangements of the pans are shown in Figs. 5 and 6. In Fig. 5 a staggered configuration was used, meant to simulate a forward motion of the robotic vehicle, while pivoting to each side (in a zigzag motion) to spread the cryogenic fluid. In Fig. 6 a bow configuration was used, meant to simulate a sweeping motion of the robotic vehicle, from one side to the other to spread the cryogenic fluid. In either case, it took on the average 7 s to extinguish each pool fire, whereas all fires were extinguished within a total of 90-95 s. The latter time includes the travel for the vehicle among the individual fires. With the established flow rate of 0.0142 L/s and a time of 7 seconds per pan, the amount of LN_2 used per unit area of pool fire was found to be approximately 1.06 L/m^2 for these tests. This is double the amount reported by Levendis and Delichatsios [4], but it is possible that a smaller amount would have extinguished the fires.

The tall sides of the roasting pans were a variable that may have affected these test results. On one hand, they might have contained the LN_2 vapors within the fire area, increasing its effectiveness; they may also have shielded the LN_2 from any wind, which could have blown it away from the fire area. On the other hand, the sides of the pan reached a fairly high temperature from the fire, and it appeared that they appeared to cause re-ignition of the flames on a few occasions.

Figure 5. Fires of iso-propanol burning in four aluminum pans in a staggered arrangement were extinguished by a remotely-controlled vehicle, which distributed LN_2 to the fires in a zigzag motion (right-left-right-left) as it moved forward.

Figure 6. Fires of iso-propanol burning in four aluminum pans arranged in an arc (bow) were extinguished by a remotely-controlled vehicle, which distributed LN_2 to the fires in a sweeping motion from right to left.

CONCLUSIONS

Previous work by the authors established that application of liquid nitrogen onto a pyrolyzing/burning surface causes an abrupt phase change, followed by a thermal expansion. The vaporizing LN_2 cools the pyrolysing/burning surface, thereby: (i) it reduces the pyrolysis rate, (ii) it forms an overhead cloud spreading by gravity, (iii) it inerts the pyrolyzate gases, and (iv) it starves the fire for air. The total expansion of the liquid nitrogen to heated gaseous nitrogen in the flame was calculated to be in the order of 1000 times. Thus, the pyolyzate gases are separated from air effectively and the fire extinguishes instantaneously. The pyrolyzing surface is subsequently blanketed for a short period of time by nitrogen gas and re-ignition is impeded.

As in the previous work this method was demonstrated by manually pouring quantities of LN_2 to the fire, this work examined application of the cryogen from a distance. A pressurized tank was used to supply LN_2, through a vacuum-insulated hose and valves to a nozzle and, therefrorm, spray the cryogen to the fire from a safe distance. However, as excessive evaporation of the volatile LN2 was encountered in flight, it was decided to forego spraying, and, instead, carry the tip of the hose right to the fire and discharge the liquid therein. To accomplish this, a prototype of a remotely-controlled unmanned robotic vehicle was constructed in-house. It was then used to suppress small pool fires, contained in four small aluminum pans (each of 0.094 m^2). Different patterns of fire extinction patterns (movements of the robot) were explored. Extinction of the fires was expedient, as it took 7 seconds to put out individual pool fires, and a total of 1.5 min to maneuver among the four pool fires and extinguish all. In addition to this time for fire extinction, the deployment time should also be accounted for, the time for the robot to reach the fire, and the initial cool-down time of the hose, will all play into the effectiveness of the system.

Implemented LN_2 flowrates were in the order of 1 L/min. Based on the results and efficacy of scale model testing, the feasibility of the concept in full scale is promising. Thus, further standardized testing is recommended to pursue this concept on a larger scale.

This system is inherently safe in that it keeps firefighting personnel at a safe distance from the fire. It will solve the problem of keeping the nitrogen in a liquid state by bringing the discharge nozzle close to the fire. The use of LN_2 on fuel storage and airport tarmac fires represents an environmentally superior option to the existing chemical fire suppressants, such as Halon and Halotron.

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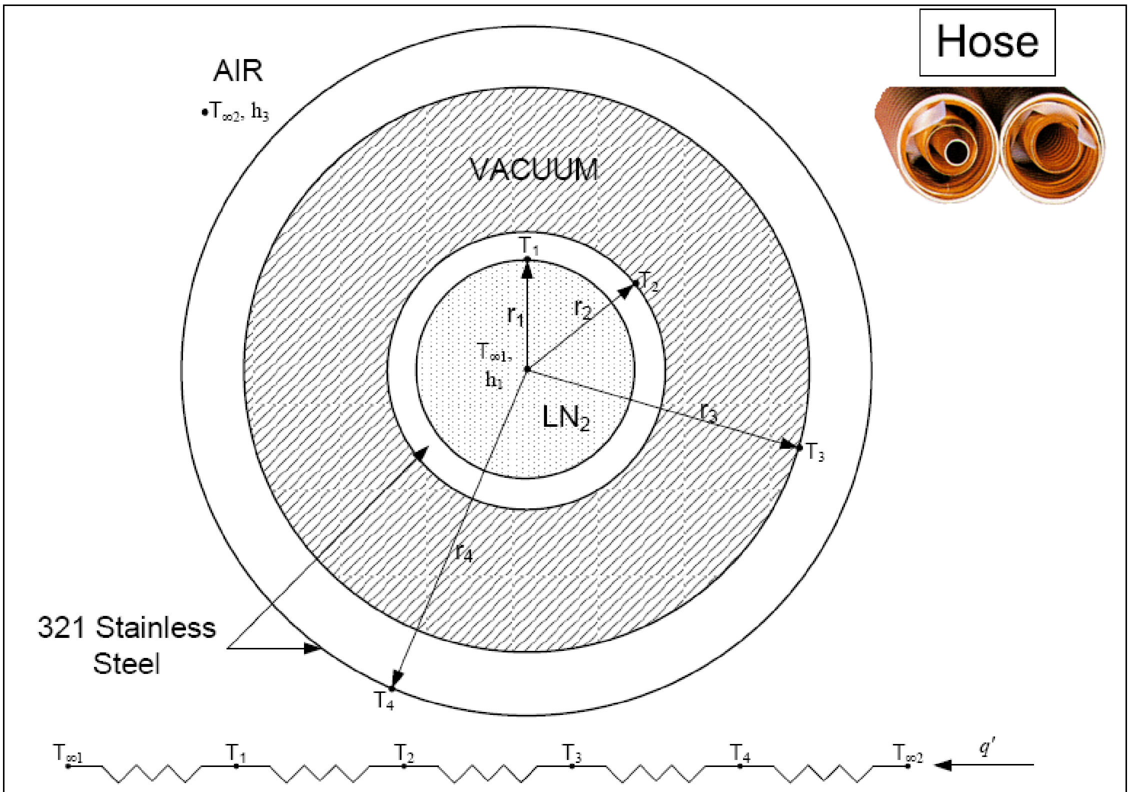

$$\frac{1}{h_1 2\pi r_1} = R_1 \qquad \frac{\ln(r_2/r_1)}{2\pi k_1} = R_2 \qquad \frac{1}{h_{2r} 2\pi r_3} = R_3 \qquad \frac{\ln(r_4/r_3)}{2\pi k_2} = R_4 \qquad \frac{1}{h_3 2\pi r_4} = R_5$$

$r_1 = 0.0159m$
$r_2 = 0.0244m$
$r_3 = 0.0318m$
$r_4 = 0.0445m$
$T_{\infty 1} = 77K$
$T_{\infty 2} = 310K$

321 *Stainless Steel*
$k_1 = 11.6 \, {}^{W}\!/_{m \cdot K}$ @ $77K$ (*estimated*)
$k_2 = 15.2 \, {}^{W}\!/_{m \cdot K}$ @ $310K$ (*estimated*)
Liquid Nitrogen
$h_1 = 1.77 \times 10^6 \, {}^{W}\!/_{m^2 \cdot K}$ (*estimated*)
Air
$h_3 = 50 \, {}^{W}\!/_{m^2 \cdot K}$ (*estimated*)

$R_1 = 5.66 \times 10^{-6} \, {}^{m \cdot K}\!/_{W}$
$R_2 = 0.0059 \, {}^{m \cdot K}\!/_{W}$
$R_3 = 223.9 \, {}^{m \cdot K}\!/_{W}$
$R_4 = 0.0035 \, {}^{m \cdot K}\!/_{W}$
$R_5 = 0.0716 \, {}^{m \cdot K}\!/_{W}$
$R_{tot} = \sum_{i=1}^{5} R_i = 223.98 \, {}^{m \cdot K}\!/_{W}$

$h_{2r} = \varepsilon\sigma(T_2 + T_3)(T_2^2 + T_3^2) = 0.02239 \, {}^{W}\!/_{m^2 \cdot K}$
$\varepsilon = 0.01$ (*Aluminum Foil*)
$\sigma = 5.67 \times 10^{-8} \, {}^{W}\!/_{m^2 \cdot K^4}$
$T_2 = 77K$
$T_3 = 310K$

$$q' = \frac{T_{\infty 2} - T_{\infty 1}}{R_{tot}} = 1.04 \, {}^{W}\!/_{m}$$

Appendix 1: Hose heat transfer calculations