

Article

A New Integrated Scheme for Urban Road Traffic Flood Control Using Liquid Air Spray/Vaporization Technology

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Abstract: With the rapid progress of urbanization, cities' demands for traffic flood control are steadily on the increase, and people are gradually paying more attention to traffic safety and environmental issues. Considering the considerable convenience and service ability of liquid air and corresponding products, people have begun to switch to using liquid air as an emergency coolant. However, this air's cryogenic operation and vigorous vaporization expansion restricts its widespread application. Our study explores innovative applications based on liquid air spray/evaporation icing and natural melting, which can be applied to urban flood protection. This study also includes a brief introduction to the nature of liquid air and road icing, a conceptual design based on liquid air flash evaporation (for urban flood protection), and the modeling and solving of natural road ice melting. This paper introduces many innovative key technologies, which include the rapid solidification of floods to form emergency ice dams or diversion channels and the application of liquid air spray to form icy roads for the temporary passage of small cars or pickup trucks. Additionally, the economic estimations are performed by using downtown traffic flood control in Wuhan as an example to showcase our innovative scheme for applying liquid air spray/vaporization for urban traffic flooding control, which is practical, pollution free, and cost effective. Our innovative scheme will be promising for flood control in modern cities.

Keywords: liquid air; road traffic engineering; liquid air spray/vaporization; icing and natural de-icing; urban traffic flooding control

1. Introduction

An urban flood may occur while the rainfall runoff exceeds the landscape's absorptive capacity or the system may change to ensure its drainage effects cannot be sufficient [1]. Since its reform and opening up in 1978, China has become an increasingly urbanized society, a factor which continues to have a profound impact on the economic growth, social progress, and improvement of life of the entire country [2,3]. However, in parallel with this process is that land use changes are related to the urban development impacts of floods in many ways [1]. As communities transform more land into roads, buildings, and other impervious surfaces, drainage systems themselves tend to become aged, undersized and unsustainable, which, in turn, makes such surfaces reach their capacity more quickly in the event of flooding, thereby destroying houses and businesses.

It is recognized that many cities in China (such as Beijing, Shanghai and Shenzhen) are facing challenges of weak infrastructure and vulnerability to flooding. The removal of vegetation and soil,

the grading of the road surfaces, and the establishment of drainage networks give rise to increasing rainfall and snowmelt on river runoff. The common consequence of urban development is an increase in the flood peak discharge and flood frequency [4–7]. In general, the annual maximum discharge of rivers will increase with an increase in urban development, although this growth will sometimes be covered by large changes during storm years, which are well marked in the annual maximum discharge of some large cities in China after 2000 [8]. In contrast, the annual maximum discharge in rural areas does not change much, even if the peak discharge, flood volume, and flood frequencies of nearby rivers increase. However, there is still no remarkable trend underlying these changes. Changes in the river course during the process of urban development will limit the flood discharge capacity of the river course. As new developments continue, roads and buildings built in flood prone areas are facing increasingly more water hazards, including floods and erosion. In addition, in recent years, urban flooding (which has been considered to occur only in a few major cities in history [9–11]) has become increasingly more serious and common in China.

Urban flooding is a type of inevitable natural disaster, but its losses can be prevented by proper control planning [12,13]. Thus, appropriate flood evacuation and disaster management plans should be made in advance in accordance with different flow conditions. Coastal urban floods are a complicated phenomenon and may occur in many forms (such as urban floods caused by high-intensity rainfall, insufficient drainage, floods caused by river or river overtopping, or floods caused by high tide). In coastal or riverside cities such as Wuhan, with river overtopping and tidal floods, serious floods will occur in most cases [14]. For effectively managing and alleviating floods in coastal or riverside cities, several strategies are often proposed to solve this problem [15]:

- (1) The Chinese government needs to further improve the urban ecological environment and ensure the effective implementation of relevant measures;
- (2) Natural water bodies must be restored and protected as soon as possible;
- (3) The permeability of urban ground should be enhanced;
- (4) The optimization of the urban drainage pipe network must achieve good correlation with the natural water system.

There are many threats caused by floods, such as the destruction of property and endangering the lives of human beings and other species [16]. Elsewhere, such as downstream or coastal areas, rapid water runoff can lead to soil erosion and associated sediment deposition. The spawning grounds in fish and other wildlife habitats may be contaminated or completely destroyed. In areas lacking elevated roads, some continuous high floods can delay traffic. Floods can damage the economic uses of land, such as drainage and agriculture. In addition to the possible damage to abutments, riparian lines, sewers, and other structures in flood channels, shipping and hydropower are often damaged. Consequently, the economic losses caused by floods are usually millions of dollars per year.

Flood control refers to all measures taken to reduce or prevent the harmful effects of floods [17]. Some commonly used flood control technologies include setting up revetments, riprap belts, or sandbags, using vegetation to maintain normal slopes or using cement soil on steep slopes and building or expanding drainage channels. Other methods include constructing dikes, dams, or detention ponds. Some flood control methods have been used for a long time. These include planting vegetation to maintain additional water, terracing hillsides to retard downhill flow and building flood control channels (artificial channels to divert flooding). There are also other technical methods and measures such as using dikes, dams, or reservoirs to maintain additional water during floods [18].

In many countries, flood-prone rivers are carefully managed [17,18]. Levees, bunds, reservoirs, and weirs are used to prevent rivers from breaking. When these defenses fail, these areas use emergency measures, such as sandbags or portable inflatable tubes. In Europe and America, coastal flooding threats have been eliminated through defensive measures such as seawalls, beach nutrition, and barrier islands. An embankment is another method of flood prevention that reduces the risk of flooding compared to other methods. It helps prevent damage, but it is best to combine dykes with other

flood protection methods to reduce the risk of dyke collapse. In China, a flood diversion area is a rural area that is deliberately submerged in an emergency to protect the city. Cleaning activities after floods often do harm to the workers and volunteers involved in the work. Potential hazards include electrical hazards, carbon monoxide exposure, musculoskeletal hazards, heat or cold stress, motor vehicle related hazards, fire, drowning, and hazardous substance exposure. Due to the instability of the flood site, cleaning personnel may face sharp serrated debris, biological hazards in the flood, exposed wires, blood or other bodily fluids, and animal or human remains. Helmets, goggles, heavy duty work gloves, lifejackets, and waterproof boots with toes and briochs are provided for construction personnel when implementing flood response measures [19].

To the best of our knowledge, there is no paper in the literature specifically devoted to a study on the application of liquid air for urban traffic flooding control. Although much attention has been given to new, fast, and pollution-free urban traffic flooding control innovation and practice, almost no information is available in the literature regarding liquid air application for urban traffic flooding control. Therefore, the application of liquid air spray/vaporization-based icing and natural de-icing offers a potentially a revolutionary contribution to urban traffic flooding control with great advantages.

With the exception of the introduction and conclusions, the main body of this study is structured as follows:

Section 2: Conceptual developments;

Section 3: The innovation of the application of liquid air spray/vaporization for urban traffic flooding control;

Section 4: The economic estimations of our urban traffic flooding control scheme based on liquid air spray/vaporization by using the downtown traffic flood control in Wuhan as an example.

2. Conceptual Developments

2.1. Description of Liquid Air

Air is composed of about 78% nitrogen and 21% oxygen, so it has similar thermodynamic properties to nitrogen. Liquefied air reduces air volume by about 700 times. Liquid air is air that is cooled to a very low temperature in order to condense it into a light blue flowing liquid [20]. Liquids are generally used to condense and/or solidify other substances and are also used as industrial sources of nitrogen, oxygen, argon, and other inert gases. Through the process of air separation, air is separated into the main components of industry, usually nitrogen and oxygen, sometimes including argon and other rare inert gases. The most commonly used method is fractionation. In order to achieve good efficiency, the heat exchanger and separation tower should be combined closely. All the energy used for refrigeration is provided by the air at the inlet of the compression device. Low temperature air separation equipment is used to provide nitrogen or oxygen and is usually used to produce argon at the same time [20]. High purity oxygen, nitrogen, and argon need to be made by the low temperature distillation of semiconductor devices. Similarly, the use of at least two distillation columns to distill the air is the only viable source for the rare gases such as neon, krypton, and xenon. Other methods, such as membranes, pressure swing adsorption (PSA), and vacuum pressure swing adsorption (VPSA), are commercially used to separate single components from common air.

The density of liquid air is about 870 kg/m^3 , but this density can be changed according to the element composition of the air. Since dry gas air contains about 78% nitrogen, 21% oxygen, and 1% argon, the density of the liquid air in the standard component can be calculated according to the percentage of each component and its respective liquid density. Although there is a small amount of carbon dioxide in the air (about 0.04%), the gas sublimates (directly transforms between a gas and a solid, so it does not exist in a liquid state), and its pressure is less than 5.1 atmospheric pressure units. The boiling point of liquid air between liquid nitrogen and liquid oxygen is $-194.35 \text{ }^\circ\text{C}$. However, when the liquid boils, it is difficult to maintain a stable temperature, because nitrogen boils first, which enriches the mixture with oxygen and changes its boiling point. In some cases, this may also occur

when liquid air condenses oxygen out of the aerosphere. In addition, liquid air freezes at approximately 58 K ($-215\text{ }^{\circ}\text{C}$) under standard barometric pressure.

As the liquid air evaporates at $-196\text{ }^{\circ}\text{C}$, the heat required for regasification of the liquid air can be completely obtained from the environment, or industrial low-grade waste heat can be used. Combined with the current market demand, the liquid air supply should be located near the demand (especially in the case of an emergency). In the manufacturing process, because oxygen is particularly suitable for gas welding and gas cutting, liquid air products are fractionated into liquid or gaseous component gases, while tungsten gas-shielded welding uses argon as oxygen in addition to a shielding gas. Liquid nitrogen has a wide application prospect in all types of low temperature situations. It is not active (unlike oxygen) at room temperature and boils at 77 K ($-196\text{ }^{\circ}\text{C}$). Large industrial users near the plant can receive separated air products through pipes. The long-distance conveyance of related products refers to the bulk conveyance of liquid products, such as Dewar bottles or small batch cylinders, or tanks used for short-distance conveyance and distribution.

2.2. Road Icing

For icing, any ice that occurs on the earth's continent or surface water is formed when a large amount of liquid water freezes and remains solid for a period of time. Common examples include glaciers, icebergs, sea ice, seasonally frozen ground, and the ground ice associated with permafrost—i.e., the perennially frozen soil found in frigid regions.

In our opinion, road icing is usually caused by snow. However, the type of freezing rain called "black ice" is the most dangerous and terrible form of road ice. Due to the concealment and accidental factors of freezing rain, the number of accidents and casualties in the process of freezing rain are much higher than those of any other type of road ice (including rain and snow). When raindrops arrive from the upper warm air layer (middle atmosphere) to the sub low temperature air layer, freezing rain/drizzle will form. When this rain drops on the ground, it creates frost on whatever it touches, forming a smooth layer of solid ice that covers everything on the ground. Black ice is the smoothest type of ice and produces almost no friction with a vehicle's tires. When the traction of a vehicle's tires approaches zero, it is almost impossible to correct a slip on black ice. Even when driving at low speed, "black ice" also has the possibility to cause the vehicle to lose control. This substance is called "black ice" because it looks very black, almost like a wet road. This "black ice" will only appear on dark surfaces, such as asphalt and concrete; "black ice" may also appear gray or tan (the same color as the pavement) [21].

2.3. Conceptual Liquid Air-Based Flash Freezing of Water for Urban Traffic Flooding Control

Freezing is a phase change. When the temperature of the liquid drops below the freezing point, the liquid becomes a solid. According to the internationally recognized definition, freezing refers to the solidification phase transformation of liquid or other substances caused by cooling. The fact that water swells when frozen causes icebergs to float. The fact that water reaches its maximum density at about $4\text{ }^{\circ}\text{C}$ causes a body of water to freeze at the top first. Then, as part of the phase transition, further expansion keeps the mass of ice above 8%. Expansion during the phase transition can be shown on the Pressure–Volume–Temperature (PVT) surface, which is the opposite of the contraction during the freezing of most substances. The expansion during freezing comes from the crystallization of water into an open hexagon. This hexagonal lattice requires more space than a liquid crystal lattice. From approximately 273 K to 72 K, hexagonal ice is the dominant form [22].

In addition, rapid freezing refers to the process of freezing an object at a low temperature of $-196\text{ }^{\circ}\text{C}$ or within a few hours of direct touch with liquid nitrogen. When the water is subcooled below $-48\text{ }^{\circ}\text{C}$, the water must be frozen. In the physical and chemical world, freezing is a natural phenomenon, which is often used for predictions in the food industry and by meteorologists. This process is also very important in atmospheric science because it is very necessary to study the appropriate climate models for the formation of ice clouds in the upper troposphere. Ice clouds effectively scatter the

incident solar radiation and prevent the earth from overheating by the sun. There is a close relationship between flash freezing and the classical nucleation theory, which helps us understand many materials, phenomena, and theories. Frozen water is a key problem for the climate, geology, and life. Winter snow covers 10% of the earth's surface, while the northern hemisphere covers 50%. The polar ice sheet can reflect up to 90% of solar radiation. The science of freezing water is decided by a number of factors, including how the droplets freeze, how much water is in the atmosphere, if the water is liquid or crystalline, the freezing temperature, and whether the water crystallizes from the inside or from the surface. The freezing of nano droplets or silicon droplets often starts near the center of the droplets, which has provided new insights into a long-standing controversy in the field of material and chemical physics. When water is put into a traditional refrigerator, it triggers a dynamic phase transition. The resulting ice is decided by the cooling rate of the system: if the water cools slowly under its freezing point, ice crystals will form instead of polycrystalline solids that freeze [23].

Water is cooled under its freezing point due to supercooling. However, if the defects are too small to crystallize, the water will remain a liquid. Therefore, a delay can be observed until the water is adjusted to a new temperature below the freezing point. Because of the extreme cold and the physical changes in the molecular structure of water, which form a tetrahedral shape, each water molecule is loosely combined with four other molecules, and the supercooled liquid water will become ice at $-48\text{ }^{\circ}\text{C}$. This shows a structural change from liquid to "medium ice". Ice crystals in supercooled water are usually triggered by a process called nucleation because the rate and size of nucleation takes place within nanoseconds and in a range of nanometers.

The environment of the surface does not play a key role in the conformation of ice and snow. Fluctuations in the density of water droplets cause possible frozen areas to cover the middle and surface areas. Surface or internal freezing may be random. However, in this strange water world, theoretically, there is still a trace amount of liquid water. Even if the temperature is lower than -48 degrees Celsius, almost all of the water will become solid or crystalline ice or non-shaped water. Below -48 degrees Celsius, the ice will crystallize too quickly to measure any properties of the remaining liquid. The nucleation process and ice crystal size are directly affected by the freezing speed. When super cooled liquid has little chance of nucleation, it will remain liquid below its normal freezing point; in other words, it will remain liquid when it is pure enough and has a smooth enough container. Once excited, it will soon become solid. In the last period of freezing, a drop of ice forms a sharp tip, which is invisible in most other liquids because water expands when frozen. Once the liquid freezes completely, the tip of the droplet attracts water vapor from the air, just as the sharp end of a metal lightning rod attracts electricity. Water vapor gathers at the top, and a small ice crystal tree began to grow. We can also preferentially extract water molecules from the sharp edges of potato wedges in an electric oven [23]. If a small drop of water cools quickly, it will form glass (low-density amorphous ice), and the water molecule tetrahedrons inside it will not be aligned but amorphous. The change in the water structure controls the speed of ice formation.

Liquid air is not only an effective and convenient refrigerant due to its availability, low cost, and friendliness to humans and the environment, but also a practical refrigerant pressure in most low-temperature applications due to its extremely low flash temperature (78.9 k) and high cooling capacity in the atmosphere. Even under high pressure, its good thermal performance makes it an effective refrigeration medium, which can quickly cool the process to low temperatures. Several cooling technologies make use of the cooling capacity of liquid air in batch or continuous processes. Among them, the direct injection/spray cooling of liquid air is a better choice for urban traffic flood protection. Liquid air is directly injected or sprayed into the flood area of the road so that the accumulated water becomes cooled and solidified by the latent heat of liquid air vaporization. According to the design of the cooling system, the sensible heat capacity of cold vaporized air may also facilitate cooling. This is an effective use of the cooling value of liquid air.

As shown in Figure 1, water freezes and ice expands instantaneously when liquid air is sprayed onto a catchment region. Icing occurs initially at $0\text{ }^{\circ}\text{C}$ and then becomes characterized by a single

indefinable surface, since ice expands to infinity in all but one direction. Due to the sudden temperature drop on the surface, the upper layer of ice undergoes transient one-dimensional conduction. Based on classical heat transfer theory, semi-infinite solids provide useful idealized methods for many practical problems. In this regard, this theory can be used to determine the transient heat transfer effect near an icy surface or the transient response of an approximately finite ice block. For the latter, an approximation is reasonable for the early part of the transition, during which the temperature inside the ice (fully removed from the surface) is not affected by changes in the surface conditions.

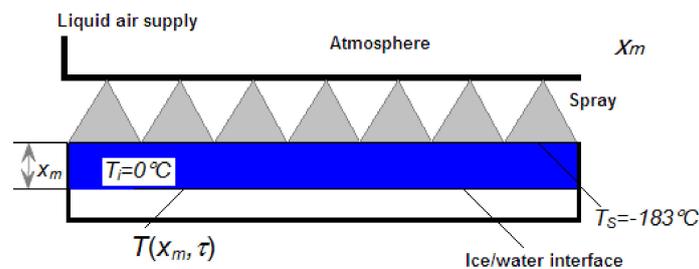


Figure 1. Schematic diagram of semi-infinite icing for spraying liquid air onto water.

Under the condition of a constant surface temperature, the heat equation of transient conduction in a semi-infinite ice block is given by [24]:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a} \cdot \frac{\partial T}{\partial t} \quad (1)$$

where a and t represent the thermal diffusivity of ice and the evolution of time, respectively.

To solve the temperature distribution ($T(x, t)$) of Equation (1), its initial conditions and two boundary conditions must be specified. The former is assumed to be the icing temperature:

$$T(x, 0) = T_i = 0 \text{ } ^\circ\text{C}. \quad (2)$$

Moreover, the interior boundary condition that ensures the ice/water interface should be at least $0 \text{ } ^\circ\text{C}$, and the lower part should be full of water, is prescribed by the following equation:

$$T(\infty, t) = T_i = 0 \text{ } ^\circ\text{C}. \quad (3)$$

Because the upper ice is always in contact with vaporized air, its surface boundary condition is assumed as

$$T(0, t) = T_s = -183 \text{ } ^\circ\text{C}. \quad (4)$$

The solution is presented as follows [24]:

$$\frac{T(x, t) - T_s}{T_i - T_s} = \text{erf}\left(\frac{x}{2\sqrt{at}}\right) \quad (5)$$

$$q_s(t) = -k \left. \frac{\partial T}{\partial x} \right|_{x=0} = \frac{k(T_s - T_i)}{\sqrt{\pi at}} \quad (6)$$

where q_s is the heat flux at the upper icing surface, and k is the thermal conductivity of ice. The function $\text{erf}(w)$ is defined as $\text{erf}(w) = \frac{2}{\sqrt{\pi}} \int_0^w e^{-v^2} dv$.

In general, an ice block whose thickness is at least 20 cm can safely support small cars or pickups. When the observable heat changes in liquid air, ice, and water are compared to their powerful latent heat ones, air flash freezing and icing processes dominate the transmission of energy. $\text{erf}\left(\frac{x_m}{2\sqrt{at}}\right) = 1$ corresponds to $\frac{x_m}{2\sqrt{at}} = 3.06$ (ice: $a = 1.002 \times 10^{-6} \text{ m}^2/\text{s}$ @ $0 \text{ } ^\circ\text{C}$); namely, $x_m = 6.124 \sqrt{at}$ is plotted in

Figure 2, which indicates that the ice formation thickness would increase to 20 cm after spraying liquid air for about 18 min. At this point, small cars or pickups could pass through the ice coverage block. This period should be short since all the conditions for spraying liquid air should be ready in advance. The mean actual temperature of the ice coverage should be below 0 °C, and the liquid air-based icing thickness should be more than 30 cm to ensure the safe passage of small cars or pickups, while the natural meltdown of ice coverage should be very slow.

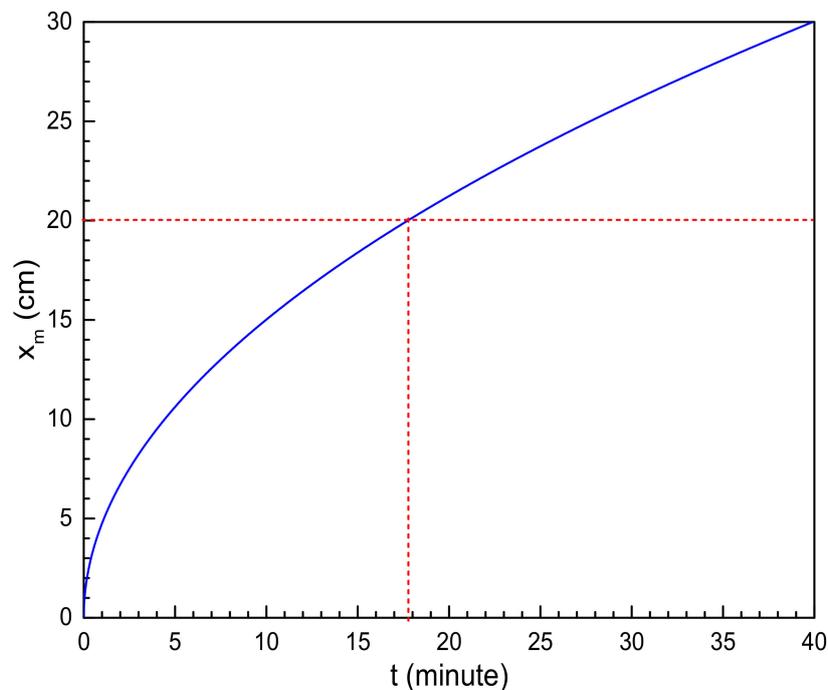


Figure 2. Icing thickness (x_m) vs. time (t).

2.4. The Modeling and Solution of Natural Road De-Icing

De-icing is the process of removing snow, ice, or frost from a surface. It is understood that anti-icing refers to the application of chemical substances, which can not only remove ice but also remain on the surface and continue to delay the transformation of ice for a certain period of time or prevent ice from sticking, making mechanical removal easier.

Road deicing is traditionally done with salt, which is spread by a snow remover, salt spreader or mud spreader that is specially used for sanding smooth roads. Sodium chloride (rock salt) usually has a wide range of application prospects because it is cheap and plentiful. However, because brine is frozen at -18 °C, it will not work when the temperature drops below this point. It is also very corrosive and rusts the steel used by most vehicles and the steel bars in concrete bridges. Different concentrations correspond to different properties. In some concentrations, this salt may be toxic to some animals and plants, so some urban areas need to stay away from it. The snowmelt also uses other salts, such as calcium chloride and magnesium chloride, which not only reduces the freezing point of water to a lower temperature but also produces exothermic reactions. These salts are safer on sidewalks, but excess amounts should still be removed.

Recently, organic compounds have been developed that can reduce environmental issues associated with salt; when used on the highway, these compounds usually include saline or solids with a long residual effect. These compounds are usually byproducts of agricultural production, such as the production of ethanol from beet refining or distillation processes. Other wood ashes and organic compounds include calcium magnesium acetate, known as deicing salts, which are made from leftover grass on the side of the road.

For liquid air-based icing for the rapid recovery of the safe passage of small cars or pickups, the safety allowance part of ice naturally melts to liquid water at a temperature of 0 °C in the air. For the establishment of a mathematical model, a clear picture of the underlying assumptions is necessary to focus on the natural ice melting process. The following assumptions are made:

- (1) Water and ice are separated by an interface;
- (2) The densities (ρ_{Water} and ρ_{Ice}) are constant;
- (3) Ice also has a constant melting temperature (0 °C) and latent heat L ;
- (4) The thermal conductivity k_L, k_S and specific heat c_L, c_S of each phase are opposite constants but have $k_L \neq k_S$ and $c_L \neq c_S$;
- (5) Only isotropical conduction (i.e., equal in all directions) occurs;
- (6) Any internal heat transfer by convection or radiation is ignored;
- (7) No consideration is given to subcooling, gravity, elasticity, or electromagnetic effects (the only exceptions are the chemical effects when foreign substances (such as salt) are added to water);
- (8) The water–ice interface should be sharp, flat, free of surface tension, and zero in thickness.

For our melting process, the study domain (Ω) is divided into water and ice regions separated by an interface $h(t)$ (Figure 3). For the sake of simplicity, the melting process on an ice block of length occurs in the one-dimensional area [$\Omega = (0, l)$] of the cross-sectional area A . The temperatures at the upper boundary ($T_A > T_{Interface}$) and lower boundary ($T = T_\infty$) are applied. The molten water in the subregion ($0 < x < h(t)$) is then separated from the ice in the subregion ($h(t) < x < l$) by a sharp interface ($h(t)$). These two stages have their own temperature distributions, $T_{Water}(x, t)$ and $T_{Ice}(x, t)$, and the lower boundary temperature is always taken as 0 °C.

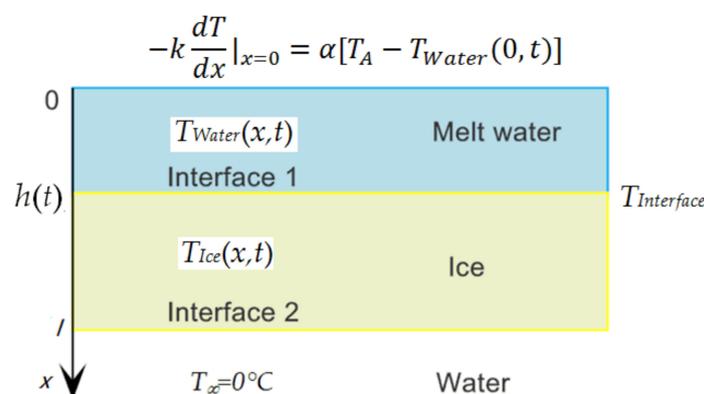


Figure 3. Ice with interface $h(t)$ and imposed boundary temperatures.

For each $t > 0$, the melting water and ice occupy $[0, h(t))$ and $(h(t), l]$, respectively. The interface position is represented by $h(t)$, which leads to two-level Stefan mathematical physics. This one-dimensional classic Stefan problem is a well-known example of a moving boundary problem. The mathematical models of solidification, combustion, flow through porous media, and molecular diffusion also feature some of these problems. Therefore, the heat equation for two phases is given:

$$\begin{aligned} T_{Water}(x, t) &= a_{Water} \frac{d^2 T}{dx^2} \text{ for } 0 < x < h(t), t > 0 \\ T_{Ice}(x, t) &= a_{Ice} \frac{d^2 T}{dx^2} \text{ for } h(t) < x < l, t > 0. \end{aligned} \quad (7)$$

The interface conditions are

$$\begin{aligned} T(h(t), t) &= T_{Interface} \text{ for } t > 0 \\ \rho L \frac{dh(t)}{dt} &= k_{Ice} \frac{dT}{dx}(h(t), t) - k_{Water} \frac{dT}{dx}(h(t), t) \text{ for } t > 0. \end{aligned} \quad (8)$$

The initial conditions are

$$\begin{aligned} h(0) &= 0 \text{ (No ice is initially melted)} \\ T(x, 0) &= T_{init} < T_{Interface} \text{ for } 0 \leq x < l. \end{aligned} \quad (9)$$

The boundary conditions are

$$\begin{aligned} T(0, t) &= T_A > T_{Interface} \text{ for } t > 0 \\ T(l, t) &= T_\infty = 0^\circ\text{C} < T_{Interface} \text{ for } t > 0. \end{aligned} \quad (10)$$

Since $\rho_{Water} > \rho_{Ice}$ represents water and ice, the former occupies less volume than the latter, so a gap is formed between the $x = 0$ boundary and the second interface $s(t)$ through the melting process. A common simplification of the above two-phase Stefan problem is the assumption that the slab is initially solid at melting temperature $T_{init} = T_{Interface}$, which means that only one phase is considered active. Since the boundary at $x = l$ is no longer important, the plate can be regarded as a semi-infinite body, so the domain Ω is $[0, l)$. This leads to a single-phase Stefan problem, which is solved by the temperature distribution $T(x, t)$ and the interface position $h(t)$, which meets the following conditions:

$$T_t = a_{Water} \frac{d^2 T}{dx^2} \text{ for } 0 < x < h(t), t > 0 \quad (11)$$

$$\begin{aligned} T(h(t), t) &= T_{Interface} \text{ for } t > 0 \\ T(0, t) &= T_A > T_{Interface} \text{ for } t > 0 \end{aligned} \quad (12)$$

$$\frac{dh(t)}{dt} = -\alpha_{Water} \frac{dT}{dx}(h(t), t) \text{ for } t > 0. \quad (13)$$

For a one-dimensional semi-infinite body whose upper surface experiences convection with ambient air, the temperature distribution $T(x, t)$ is solved as follows [24]:

$$\frac{T(x, t) - T_{Interface}}{T_A - T_{Interface}} = \operatorname{erfc}\left(\frac{x}{2\sqrt{at}}\right) - \left[\exp\left(\frac{\alpha x}{k}\right) + \left(\frac{\alpha^2 at}{k^2}\right)\right] \operatorname{erfc}\left(\frac{x}{2\sqrt{at}} + \frac{\alpha\sqrt{at}}{k}\right) \quad (14)$$

where the complementary error function ($\operatorname{erfc}(w)$) is defined as $\operatorname{erfc}(w) = 1 - \operatorname{erf}(w)$, and the natural convection coefficient α is defined by [24]:

$$Nu = \frac{\alpha L}{k_{Air}} = 0.27 \sqrt[4]{GrPr}, \quad 10^4 \leq Gr, \quad Pr \leq 10^{10} \quad (15)$$

where L is the characteristic length, which is taken as the length for a general bridge water pit.

The following algorithm, which takes the melting point depression into account, is applied to numerically solve the above control equations. For each timestep, the following items should be updated:

- (1) The temperature distribution based on the application of Equation (11);
- (2) The boundary state based on the application of Equation (12);
- (3) The melting point $x, t + \Delta$.

For steps (1) and (2), the finite difference method (FDM) is used. For step (1), we use the implicit scheme:

$$\frac{T(x, t + \Delta t) - T(x, t)}{\Delta t} = \alpha \frac{T(x - \Delta x, t + \Delta t) - 2T(x, t + \Delta t) + T(x, t + \Delta t) - T(x + \Delta x, t + \Delta t)}{(\Delta x)^2}. \quad (16)$$

In step (2), we use an explicit method:

$$\frac{h(t + \Delta t) - h(t)}{\Delta t} = -\alpha \frac{T(h(t), t) - T(h(t) - \Delta x, t)}{\Delta x}. \quad (17)$$

To find a way to solve this problem for an initial non aquifer and a temperature $T_A = 303$ K, the considered space is 0 to 30 cm. The initial temperature distribution should obey the following analytical solutions:

$$T(x, 0) = \begin{cases} T_A - \Delta T_{Water} \operatorname{erf}\left(\frac{x}{2\sqrt{at_0}}\right) / \operatorname{erf}(\phi) & (0 \leq x \leq h(0) = h_0) \\ T_{Interface} & (x > h_0) \end{cases} \quad (18)$$

where ϕ is the solution of the equation $(\phi \exp(\phi^2) \operatorname{erf}(\phi) = c_{Water} \Delta T_{Water} / (\sqrt{\pi} L))$, and $t_0 = h_0^2 / (4a\phi^2)$.

In general, keeping roads open and safe under various winter conditions is a top priority for road management, but ensuring ice-free pavement conditions can be a challenge, especially when unpredictable storm conditions affect staff, equipment, and budgets. In contrast, liquid air spray-based icing helps to ensure emergent car or pickup traffic under any urban flooding. Icing requires a relatively short period of time, but natural ice melting lasts for a long period of time. Liquid air spray actually results in the formation of subcooled ice, which may significantly reduce the melting rate and lead to a steady state in which the position and shape of the solid-liquid interface are both primarily dictated by the subcooling parameters.

The water-ice interface position's evolution as a function of time is plotted in Figure 4, where the upper ice (thickness: 10 cm) in our study case melts after about 44 min. At this point, the ice block, whose liquid air-sprayed icing thickness is 30 cm, reaches its thickness threshold for the passage of small cars or pickups.

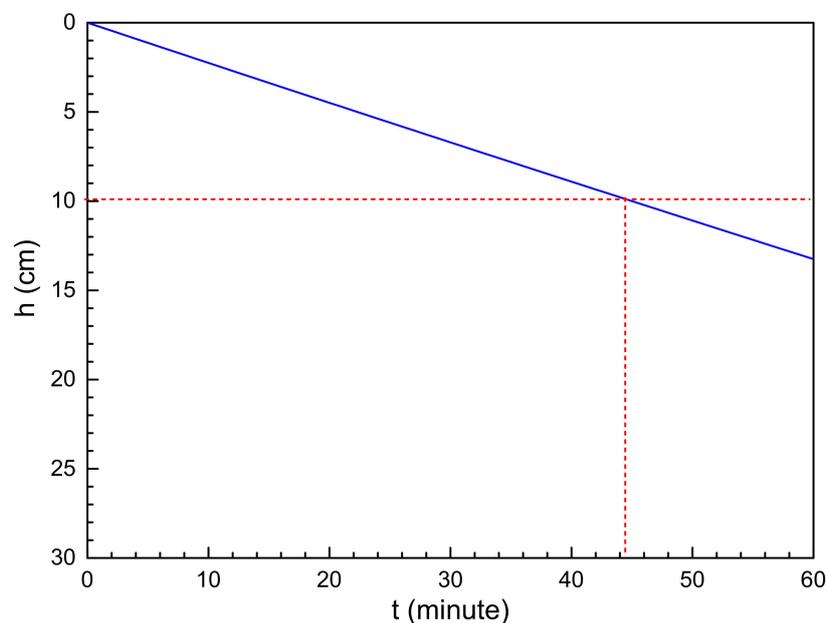


Figure 4. Water-ice interface $h(t)$ vs. time.

3. Innovation of the Application of Liquid Air Spray/Vaporization for Urban Traffic Flooding Control

Here, some innovative applications of liquid air spray for urban traffic flooding control are presented, including liquid air spray-based icing for the rapid formation of temporary ice roads for small cars or pickups, the rapid solidification of flood water for the production of emergent ice dams or diversion channels, the rapid diversion of rain clouds based on the vaporization of liquid

air, and a technique for assembling open diversion channels. Thus, a new conceptual emergency floodwater prevention and control system scheme for modern cities based on the application of liquid air spray-based icing and natural de-icing is presented in this study, which includes the above four techniques, which are schematically shown in Figure 5.

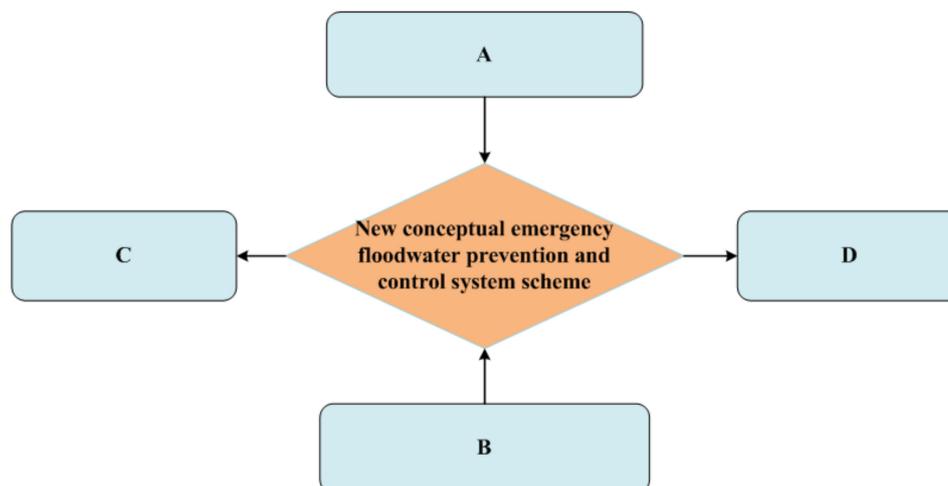


Figure 5. New conceptual emergency floodwater prevention and control system scheme for modern cities based on the application of liquid air spray-based icing and natural de-icing. A is the liquid air spray-based icing for the rapid formation of temporary ice roads for small cars or pickups. B is the rapid solidification of flood water for production of emergent ice dams or diversion channels. C is the rapid diversion of rain clouds based on the vaporization of liquid air. D is the technique of assembling open diversion channels.

3.1. Liquid Air Spray-Based Icing for the Rapid Formation of Temporary Ice Roads for Small Cars or Pickups

It is well known that ice caps formed on waterbodies like rivers and lakes are capable of supporting loads within the limits of their load bearing capacity. Natural ice is buoyant and floats on water because its density is 8%–10% lower than water. At any urban traffic flooding point, ice can be quickly formed by spraying the area with liquid air (especially by injecting liquid air into the flood) to create a flat, smooth driving surface without trees, rocks, or other obstacles, thereby providing temporary access for small cars or pickup trucks. Icy roads provide the best method for mobile heavy equipment and workers to cross areas without roads while protecting the fragile ground below.

When any ice sheet based on the liquid air jet is located above deep water, this sheet will generate the corresponding buoyancy, which will sustain the gravity of the ice load. When the ice sheet itself is bent under this load, it will replace the water equal to the load weight according to the Archimedes principle. In theory, the amount of water and the size of the ice sheet must be large enough to support the load on the ice sheet. However, most water bodies are not large enough relative to the load, so it is necessary to detect the buoyancy in practice. The key problem is to determine whether the ice sheet can withstand the load caused by temporary bending to judge whether it is strong enough.

Although an ice sheet looks solid, it bends when it is under a load. The deflection and load of ice are the influencing factors of its bending amount. The greater the load, the greater its bending and displacement. For acceptable loads, when the load is removed or moved, the ice sheet bounces back to its original position. In this case, the ice sheet will deform and distribute its load to a larger acreage. The depressions under this load are often referred to as deflection bowls. Ice may collapse due to various causes. Some of the common failures include loads of poor ice, an overload of high-quality ice, the excessive stress of ice when running at an unsafe speed, and unexpected fixed loads on the ice.

In contrast, most ice caps based on liquid air jets are located in shallow water, so there are various dangers in working on these ice caps. The main ice cover hazards include: (1) working on a damaged ice cover, (2) overloading the ice cover beyond its load-carrying capacity, and (3) working

in an undetected thin ice area. These threats can be avoided through a variety of engineering and management measures that will give the operator enough confidence to (1) test the integrity of the ice sheet, (2) understand the load on the ice sheet, and (3) determine the minimum ice thickness. A conceptual ice road view is shown in Figure 6.

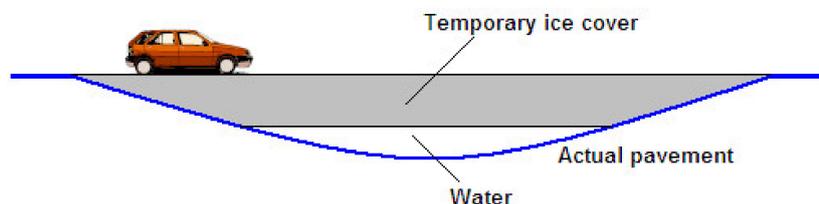


Figure 6. A conceptual ice road view.

With confidence in these three elements, ice operations can be carried out very safely. In areas with dry cracks more than 10 cm wide, the cracks should be repaired by spraying or filling with liquid air to allow them time to completely freeze. Alternatively, the reduction in the maximum load limit should be considered. The decision to reduce the load limit will be based on the frequency, width, depth, and intersections of the cracks. Once the cracks are completely refrozen by spraying or filling them with liquid air, the ice can become as hard as it was before the cracks occurred.

Some ice roads that form cracks over very shallow water may be utilized to ensure the continuous stream of cars, as driving on cracked ice may be preferable to driving over bumpy roads. This driving may last longer since natural de-icing is a slow process. Moreover, liquid air spray-based icing may be repeated in the case of more ice melting.

Knowing how to drive in an icy environment is an extremely important skill. Ice floes create dangerous driving conditions and may cause serious accidents. When a vehicle is driving on ice, the vehicle will not follow the usual laws of physics. For example, a car will drive straight on a curve, no matter how much the driver turns the steering wheel; inertia makes the car move in that direction, but frozen tires can help solve this problem. There are also warnings given by local transportation authorities to drivers, but in the case of ice, these warnings are often not sufficient. Some practical driving techniques include the following: do not step on the brakes, drive slowly, gradually change directions, avoid fishtailing, do not follow other cars too closely, and take emergency measures in the worst-case scenario to help avoid accidents in icy conditions.

3.2. Rapid Solidification of Flood Water for Production of Emergent Ice Dams or Diversion Channels

Generally, when ice floes accumulate in a natural or man-made way, preventing them from developing downstream, ice jams occur in rivers. Ice plugs can significantly reduce river flow and cause upstream floods, which are sometimes called ice dams. When ice plugs are released in an eruptive flood, ice plug floods may also occur downstream. In either case, floods can cause damage to buildings on the shore. However, the diversion dam here diverts all or part of the river's flow from its natural route. Diversion dams generally do not store water in reservoirs; instead, they move water into artificial channels or canals. It is challenging and important to extract floodwater from a traffic-stagnant water point. Keeping floodwater out of urban traffic-accumulated storm water locations is essential to preserving smooth traffic from the destruction caused by flooding. While there is no surefire way to guard against flooding, flood diversions can improve the traffic's chances of surviving intact.

Freezing flood prevention and the protection system based on liquid air spray aims at the immediate control, protection, and prevention of flooding problems. In essence, one such flood protection system is equivalent to many sandbags. These systems are environmentally friendly, reusable, modular, and can meet the protection requirements. Ice dams or diversion channels may be rapidly produced based on the rapid solidification of flood water due to the tremendous heat transfer temperature difference by means of the vaporization of liquid air flowing through the roadside

pipe fences onto which floodwater is pumped. They may be utilized to pump the accumulated floodwater out and to ensure smooth traffic. Moreover, such ice may be transferred to application fields, such as freezers, ice storage air conditioning systems, and crematoriums for cold energy utilization. The schematics for retaining dams and the diversion channels of ice are shown in Figure 7.

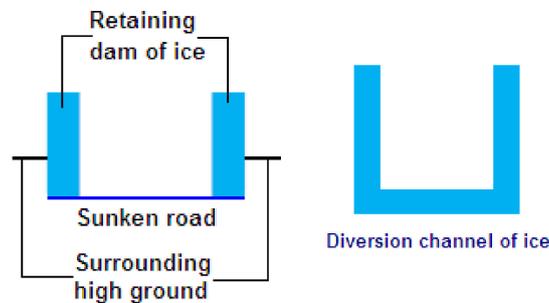


Figure 7. Schematics for retaining dams and diversion channels of ice.

3.3. Rapid Diversion of Rain Clouds Based on the Vaporization of Liquid Air

In the blazing summer, the temperature of the earth's surface rises. The warm air formed by heating the air on the earth's surface through the conduction process rises gradually. After the warm air rises and cold air sinks, convection plays an extremely important role in the formation of strong thunderstorms. If the ground temperature continues to be high, the air will continue to rise because it is less dense than the surrounding air. It also facilitates heat transfer by convection from the surface to the upper atmosphere. The two most important factors of thunderstorm formation are instability (air instability) and moisture. Thunderstorms are mainly divided into three types according to their terrain, air quality, and frontal lobes, which are described as follows:

- (1) Orographic thunderstorms are caused by air that is forced up by a mountain or hillside;
- (2) Air mass thunderstorms are the result of the local convection of an unstable air mass;
- (3) Frontal thunderstorms occur at a frontier boundary (e.g., cold front).

Most commonly, rain clouds that produce steady rain are referred to as nimbostratus clouds. These clouds appear very low in the sky, ranging from medium to dark grey. Sometimes, stratus clouds are associated with a light drizzle. Stratocumulus clouds almost never produce rain, although they can turn into nimbostratus clouds if conditions allow. Mammatus clouds and green clouds are normally associated with severe weather, including hail or tornados. Clouds up to 18,000 feet are called cirrus clouds. Clouds from 6500 feet to over 18,000 feet are called Alto clouds. Clouds below 6500 feet are mostly stratiform and may indicate rain.

Thus, the timely dispelling of rain clouds and the prevention of cold air coming into contact with hot air are some effective methods to prevent ice production. The vaporization of liquid air or compounds indicates a strong phase change from the liquid phase to the air phase. Tremendous heat transfer temperature differences result in bulk boiling rather than surface evaporation. The vaporized air flow from the rapid solidification of flood water for the production of emergent ice dams or diversion channels is free of moisture, so its movement into the ambient air will not only decrease the relative humidity of mixed ambient air but also drive the overall upward motion of air over the storm area. Thus, the rain clouds integrating and interchanging hot and cold air streams may be dispersed or move away; moreover, local rainstorms cannot successfully occur. This technique for rapidly dispelling rain clouds based on the vaporization of liquid air is schematically shown in Figure 8.

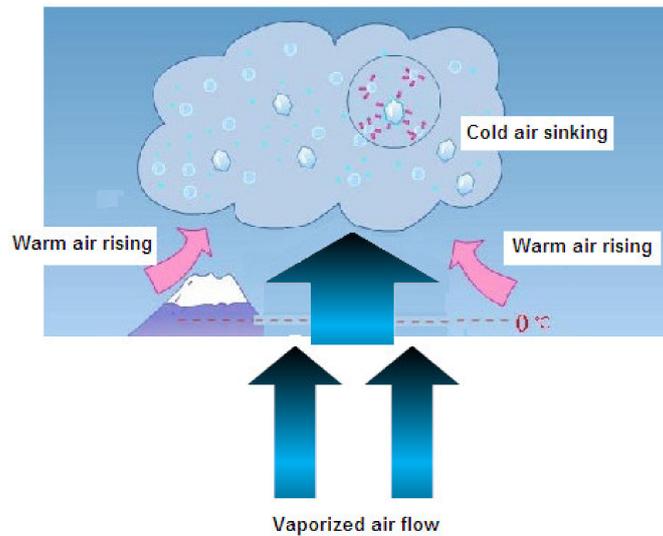


Figure 8. Rapidly dispelling rain clouds based on the vaporization of liquid air.

3.4. The Technique of Assembling Open Diversion Channels

Diversion channels or spillways are man-made channels designed to provide different flow paths for excess water, thus further reducing the impact of floods and restoring the river to its natural level. Generally, diversion channels are built around communities or economic centers to prevent flooding. These diversion channels may be formed in a short period of time by means of rapid icing based on the vaporization of liquid air. The modular diversion channels of ice (Figure 9), which can be assembled together or elevated overhead, are coupled with a mobile modular pump assembly unit so that accumulated floodwater can be pumped in a short period of time to any location that does not affect traffic. Such diversion channels for ice primarily benefit from their rapid modular production, lack of pollution and subsequent cleanup work, cooling activity, convenient and flexible assembly, short construction period, and reutilization of ice.

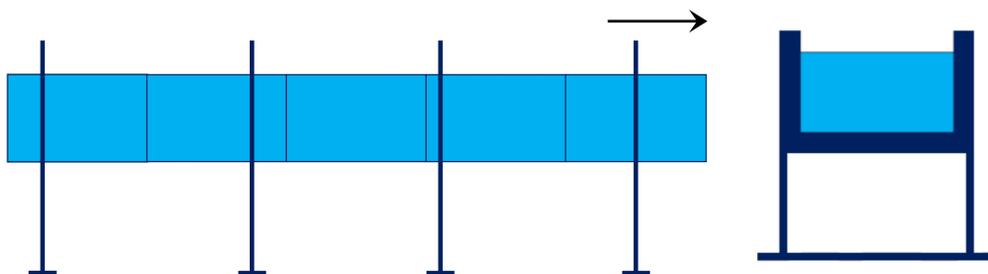


Figure 9. Assembled modular overhead diversion channels of ice.

4. The Economic Estimation of Our Urban Traffic Flooding Control Scheme Based on Liquid Air Spray/Vaporization Using Wuhan Downtown Traffic Flood Control as an Example

A few years ago, during the first commercial production of liquid air, there were many untenable claims about liquid air's practicality. One of the most valuable uses of air liquefaction is the subsequent use of fractionation and distillation to separate oxygen and nitrogen. However, it has been proven that liquid air has great value for studying the behaviors of various materials at low temperatures. For example, it is generally believed that at very low temperatures, metals can become very fragile. Specifically, in many cases, rails in winter weather are prone to fracture, and the specific reasons behind these failures can be studied with liquid air. So far, in the manufacturing process, because oxygen is particularly suitable for the welding and cutting of fuel gas, liquid air products have been divided into liquid or gaseous component gases. In tungsten electrode gas-shielded welding, in addition to

the shielding gas, separated argon is also used as oxygen. Separated liquid nitrogen has a variety of low-temperature applications; it is inert at room temperature (unlike oxygen) and boils at $-196\text{ }^{\circ}\text{C}$. A variety of liquid air applications have been developed globally. The 2019 Corporate Sustainability Report of Air Products offers a detailed account of such developments: “We bring talent together to meet the challenges facing us, our customers and our world with innovative solutions, which is another aspect of our higher goals”. Many of these challenges are related to sustainability, such as providing cleaner fuels, improving energy efficiency, reducing emissions, providing clean water and providing quality food [25].

Using Wuhan City as an example, we conducted an economic evaluation of the liquid air application of urban traffic flood control schemes in the capital cities of Hubei Province, Wuchang, Hankou, and Hanyang. Wuhan is the largest inland port in the middle reaches of the Yangtze River and the main station of the Beijing–Guangzhou Railway. It is also one of China’s largest inland port cities and the most important waterway and railway transportation hub. It has 46 easily flooded traffic locations (Figure 10) in its urban areas, based on the 2019 Easily Flooded Risk Map released by the Wuhan Institute of Water Sciences on 16 March 2019 [26]. This map indicates that Wuhan’s urban drain ability has improved significantly in recent years, so the number of flooded locations and flooding durations and areas will fall remarkably under the same conditions of rainfall. There are many factors related to this urban flooding. Respectively, 40 and 46 locations may be flooded in the case of torrential rains below 100–150 mm and above 150 mm; most of these locations are in low-lying urban areas. Except for unfavorable flood drainage factors such as increasing extreme rainfall events due to climate change and special geographical/topographical conditions, factors like the poor project construction-related operation of its drainage pipeline networks, lagged support facilities, low standard drainage facilities, and small drainage capacity primarily affect the occurrence of flooding. Targeted emergency plans and measures are currently based on a correspondingly conscientious analysis of the Wuhan Water Authority.

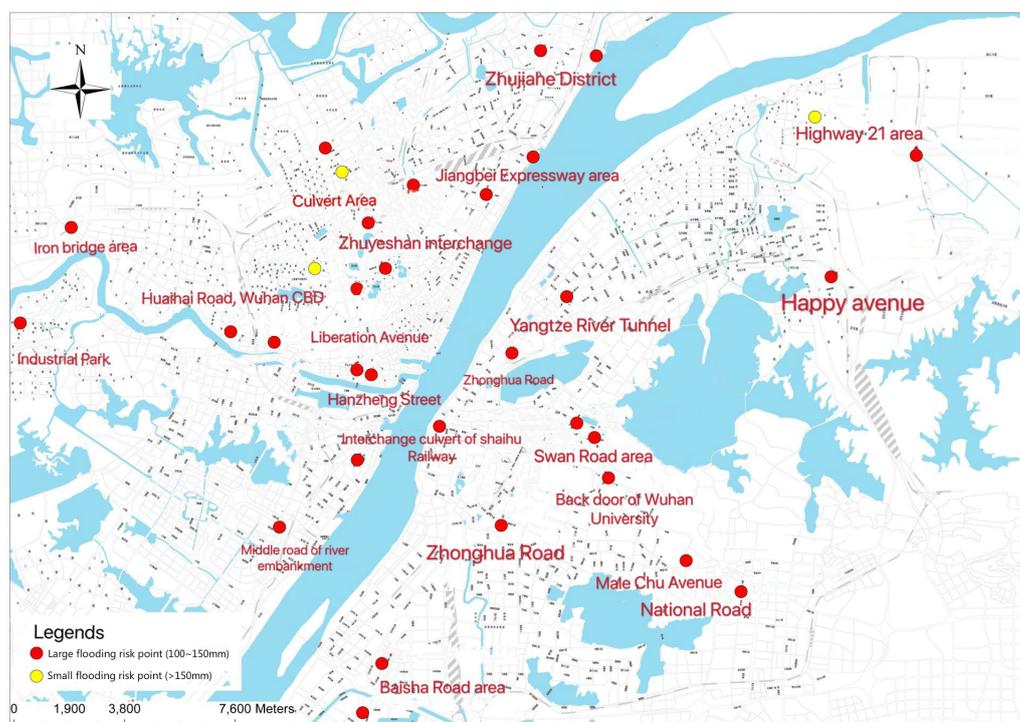


Figure 10. Easily flooded traffic locations in the urban area of Wuhan (2019).

Figure 11 presents a traffic flooding picture for a site in Wuhan on 21 June 2019, which indicates that the cars were immersed in water about 50 cm deep [27]. For this type of flooded site, it is assumed

that one diversion channel of ice (length: 700 m; weight: ~50 tons) is necessary to urgently pump water away to a field that has nothing to do with traffic, and ice sheets (area: 2000 m²; thickness: 40 cm; weight: 720 tons) are provided for emergency pedestrian paths. The total weight of the above two items may be magnified to 800 tons, including an ample margin. The production of 800 tons of ice requires about 700 tons (~780 m³) of liquid air, which may release gaseous air of about $800/0.81 \times 700 \approx 691,000$ m³ in its standard state. This amount of “boil-off” air may move the overhead rainclouds away from the sky of the flooded site. A buffer tank should be equipped on the icing site under such great gasification. Indeed, a centralized production plant can be established near the air separation unit so that the pipeline transportation may be used for the required liquid air without tank transportation. A relatively small amount of liquid air needs to be supplied to the site or reserved in a storage tank nearby the traffic flooding site, according to the site’s needs. In this scenario, the main transport costs would drop, and the rapid release of a great deal of vaporized air would cool down the hot weather and help dissipate the overhead rain clouds. Wuhan Iron and Steel (Group) Corporation (WISCO) Oxygen Industrial Gases Co., Ltd., located in Wuhan’s Qingshan District, could provide the liquid air delivery and corresponding auxiliary services, whose price is determined to be \$143/m³ liquid air; 780 m³ of liquid air costs \$111,540, which is magnified to \$1,427,838 when considering labor costs and other incidental expenses. With reference to the total of this particular traffic flooding control case, 46 easily flooded traffic locations would cost \$65,680,548 for the worst flood disaster. Moreover, most of the ice may be reused after flood control or naturally melted for urban cooling in the steamy summer. While there are two such flood disasters every year at most (according to the statistical analysis), the total costs of flood control based on our innovative approach coupled with the application of liquid air spray/vaporization-based icing and natural de-icing would reach \$131,361,015 for Wuhan (a metropolis in Central China), whose flood control funds totaled \$1,854,046,491 during the period 2016–2018. The total cost of \$131,361,015 only accounts for 21.3% of the planned flood control funds per year on average, without considering the benefits of reutilizing ice.



Figure 11. A traffic flooding site in Wuhan on 21 June 2019.

Some air product supply stations could be integrated into existing flood risk locations to cut back dependence on expensive emergency supplies. Integrating liquefied air into existing flood risk

locations solves the large challenge of establishing and improving the city's existing air product supply network. In addition, liquefied air can also be transported to other locations for further use. A liquid air economy could also be integrated into the Central China logistics network. Wuhan is a hot city in the summer and autumn, and its indoor temperature mainly depends on air conditioning. Thanks to the widespread use of air conditioners, liquid air as a coolant can be integrated effectively, since most of the cooling needs of businesses and organizations come from air conditioning. When this air conditioning needs extra power, liquid air can be used as the cooling source of the building, circulating around the building to reduce the indoor temperature. In other words, liquid air can effectively reduce dependence on the power grid in case of an emergency.

There are many potential uses for liquefied air, but like other emerging technologies, it has to "bridge the gap" from early adopters to the mass market (i.e., wide acceptance in China). Therefore, the industry and relevant companies must fully understand the economic potential, return on investment, and expected financial benefits of using liquefied air in all relevant scenarios, including commercial activities.

5. Conclusions

Over the past 40 years, China has become an increasingly urban society. Land use change related to urban development has had an impact on the occurrence of floods in many respects. Urbanization usually increases the scale and frequency of floods and may expose communities to greater flood damage. Urban flooding is one of the main causes of economic losses, social unrest, and housing inequality. This study presents a conceptual application of liquid air spray/vaporization-based icing and natural de-icing for urban traffic flooding control, which includes some advanced and innovative techniques, such as liquid air spray-based icing for the rapid formation of temporary ice roads for small cars or pickups, the rapid solidification of flood water for the production of emergent ice dams or diversion channels, the rapid diversion of rain clouds based on the vaporization of liquid air, and the technique of assembling open diversion channels. This paper explores the conceptual application of liquid air spray/vaporization-based icing and natural de-icing for urban traffic flooding control, whose conceptual developments (including descriptions of liquid air, road icing, the conceptual liquid air-based flash freezing of water for urban traffic flooding control, and modeling/solving natural road de-icing) are described and analyzed in detail. In addition, the economic estimation of our urban traffic flooding control scheme based on liquid air spray/vaporization (taking Wuhan downtown traffic flood control as an example) is presented to demonstrate that our innovative scheme will be promising for flood control in modern cities.

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