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Research paper

Meso-scale wrinkled coatings to improve heat transfers of surfaces facing ambient air

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HIGHLIGHTS

- Various wrinkled surfaces were fabricated by a practical process.
- Topographical effect on convection was parameterized separately from radiation.
- Meso-scale wrinkled coatings increased convective heat transfer with ambient air.
- Maintenance cost of outdoor steel sheets due to condensation can be reduced.

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ABSTRACT

Meso-scale (micrometer-to submillimeter-scale) wrinkled surfaces coated on steel sheets used in outdoor storage and transport facilities for industrial low-temperature liquids were discovered to efficiently increase convective heat transfer between ambient air and the surface. The radiative and convective heat transfer coefficients of various wrinkled surfaces, which were formed by coating steel sheets with several types of shrinkable paints, were examined. The convective heat transfer coefficient of a surface colder than ambient air monotonically changed with average height difference and interval distance of the wrinkle undulation, where the proportions were 0.0254 and 0.0054 $W/m^2/K/\mu m$, respectively. With this wrinkled coating, users can lower the possibility of condensation and reduce rust and maintenance cost of facilities for industrial low-temperature liquids. From the point of view of manufacturers, this coating method can be easily adapted to conventional manufacturing processes.

1. Introduction

Storage and transport facilities for industrial low-temperature liquids such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG), are often located outdoors where they are exposed to severe temperature change, solar radiation, precipitation, brine, dust, and humidity. See Fig. 1. In order to protect the liquid from such severe climates, the facilities consist of containers or pipes covered with thermal insulators and steel sheets around the insulators. The steel sheets have multi-layer coatings to avoid chemically- or mechanically-induced corrosion [1–3], such as outer paints on aluminum- or/and a zinc-alloy layer on steel substrates. The thermal insulators prevent the liquid from heating up, but, in practice, they slightly conduct heat from the outer surface to the internal liquid. This heat leakage may cause problems with regard to transportation efficiency of the liquid and maintainability of the facility equipment. In the daytime, solar absorption on the outer-cladding metal sheets brings about heating of the enclosed liquid

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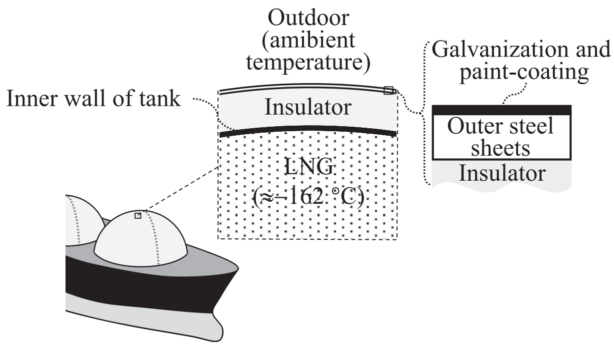

Fig. 1. Rough sketch of storage/transport facility for low-temperature liquids such as an LNG tanker. The liquid is thermally and mechanically protected from outdoor by insulators and steel sheets galvanized and paint-coated.

by thermal conduction through the insulators. Excellent solar reflective paints have been recently employed to prevent such heating. In the night, the sheet surface is cooled below the temperature of ambient air by the internal low-temperature liquid through slight thermal conduction. Such a situation increases the probability that the sheet surface is covered with water condensed from ambient air and subsequently with rust, which is a problem against long-term maintainability. Thus, the steel sheets of the facilities for industrial low-temperature liquids are desired to be condensation-proof. Several techniques have been proposed to solve the issue, such as water-repellency treatment, chemically rustproof coatings, etc. [4–6], although these techniques may be undesirable due to difficult procedures and cost in manufacturing. There has not been an approach to this problem from the point of view of surface heat transfer, especially convective heat transfer.

Heat transfer occurring at a solid surface is classified into radiation and convection. Radiation can transfer heat between thermally emissive surfaces that are divided from each other by a distance, and the transfer efficiency is proportional to the thermal emissivity of the surfaces. On the other hand, convection can transfer heat between the surface and the surrounding fluid, air in this case, and the efficiency depends not only on the properties of the fluid, such as viscosity, thermal conductivity and flow speed [7], but also on the surface characteristics such as topography and geometry [7–9]. The surface temperature is determined by the balance of thermal conduction and surface heat transfers due to radiation and convection. Thus, the appropriate design of the thermal emissivity and topography of the surface is of importance for bringing surface temperature as close as possible to ambient temperature, and consequently for reducing the possibility of condensation. Practically, thermal emissivity of the steel sheets cannot be chosen absolutely, because the appropriate value depends on the surrounding objects, such as artificial buildings, ground, sea and sky, being at various temperatures. On the other hand, convective heat transfer should be as efficient as possible under any situations, because convection reduces the temperature difference between the surface and ambient air.

Several types of meso-scale (micrometer-to submillimeter-scale) wrinkled paints were coated on metal sheets using practical methods obtained from conventional manufacturing processes [10]. Then, the convective heat transfer of the meso-scale wrinkled surfaces was experimentally analyzed. There have been investigations about the effect of surface topography on convective heat transfer in various fields [11–20]. The spatial distribution of h_c was studied experimentally for airflow in vertical channels patterned with centimeter-scale rib structures, using an optical schlieren method [12]. Furthermore, the influence of centimeter-scale undulations on h_c was simulated with several types of fluids [13,14]. A predictive model was proposed for thermal contact resistance formed at the boundary between liquid and solid phases during die-casting, and was examined in comparison with experimental analysis about convection traps [16]. Topographical effect on convective heat transfer in natural convection was found using numerical simulation by the domain decomposition method [17]. Numerical analysis concluded that surface topography increased h_c up to 1.5 times with the change in coverage of submillimeter-scale dot fouling on flat surfaces [19].

Our experiments quantified the effects of meso-scale surface topography on convective heat transfer, and provided the knowledge to explore wrinkled surface coatings. Using this work, manufacturers can optimize the topography of wrinkled surfaces to increase the convective heat transfer coefficient of the steel sheets. The coatings can control condensation from moisture in ambient air and subsequent rusting. This will decrease maintenance cost of steel sheets used in outdoor storage and transport facilities for industrial low-temperature liquids. This coating method can be easily adapted to conventional manufacturing processes.

2. Experiments and analysis

2.1. Sample preparation

Meso-scale wrinkled surfaces were formed with various height differences and interval distances of ridges and grooves by using coatings on hot-dip aluminum-coated steel sheets and by managing thermal emissivity. These methods were obtained from practical fabrication processes using shrinkable paints and aggregates [10,21]. See Table 1. Samples A to G had steep bumps, and samples H–K had gentle undulations in the surfaces. Samples L–N had thermal emissivity with a large difference from the other samples, in order to distinguish the possible influence of infrared emission on the measurements.

First of all, substrates with hot-dip aluminum-coatings on steel sheets were brushed with primer and then heat treated by hot blast at 5 m/s at 200 °C for 30 s in an oven, to form a 5-μm-thick undercoat layer for preparation of samples A–M. The primer consisted of the usual compositions used in conventional manufacturing, that is, isocyanate cross-linked epoxy-modified polyester resin as the main component, anti-corrosive pigment (magnesium hydrogenphosphate (5 wt.%), zinc phosphate (10 wt.%), and aluminum triphosphate (10 wt.%)), and color pigment (TiO_2 (15 wt.%) and

Table 1
Topographical and optical properties, and convective heat transfer. Samples A to M were coated with a flat or wrinkled paint layer and sample N was a bare aluminum sheet.

Sample	Surface property			Convective heat-transfer coefficient h_c (W/m^2/K) at θ_{si} of	
	Thermal emissivity ε	R_a (μm)	S_m (μm)	−20 °C	60 °C
A	0.910	6.74	33.81	6.68	7.06
B	0.907	8.94	79.70	7.09	7.53
C	0.903	8.54	66.33	7.06	7.72
D	0.895	14.31	99.44	7.56	8.12
E	0.893	5.76	30.29	6.83	6.99
F	0.906	8.88	53.77	6.89	7.19
G	0.901	8.99	54.52	6.78	7.27
H	0.866	1.38	71.19	6.82	6.55
I	0.875	5.16	49.47	7.21	6.65
J	0.874	4.91	60.48	6.75	6.33
K	0.885	3.35	79.58	7.01	6.29
L	0.603	1.73	39.62	6.86	7.06
M	0.734	13.23	32.60	7.05	7.27
N	0.038	1.16	26.57	6.74	6.90