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Review

A review study of solid–gas sublimation flow for refrigeration: From basic mechanism to applications

Lin Chen [a], *Xin-Rong Zhang* [a,b,*]

[a] *Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing 100871, China*
[b] *Beijing Key Laboratory for Solid Waste Utilization and Management, Peking University, Beijing 100871, China*

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ABSTRACT

Sublimation is one phase change mechanism which usually happens under low-to-moderate temperatures and at the same time large amounts of latent heat can be utilized. Low temperature sublimation has been proposed in a lot of applications as one useful cooling/refrigeration mechanisms, such as medical cooling, food engineering, chemical synthesis, domestic cooling and many industrial sectors. In this review study, the basic mechanisms of sublimation two-phase flows are firstly reviewed. In earlier years, theoretical studies focused on and analyzed surface crystal structure effect. Later, the focus was on recent developments in numerical modeling and experimental verifications. Numerical modeling studies were mainly focused on the sublimation parameter behaviors under various ambient situation and container geometries. In recent years, it is also found that multi-scale modeling has become one of the most promising topics in this field. In experimental studies, major newly developed visualization systems and related real refrigeration systems are summarized and discussed. As more and more studies proposed application systems, several representative refrigeration systems are also introduced and compared in this paper, which may give useful indications for future innovations. Future research focuses are also proposed in this review study while this field is still young (but promising), both for scientific research and real system designs. It is hoped that this brief review can contribute to the development of novel refrigeration systems and the development of cryogenic science and engineering.

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Un passage en revue de l'écoulement de sublimation pour le froid: du mécanisme de base aux applications

Mots clés : Changement de phase ; Froid ; Ecoulement dipahasique solide-gaz ; Sublimation ; Transfert de chaleur ; Synthèse

* Corresponding author. Beijing Key Laboratory for Solid Waste Utilization and Management, Peking University, Beijing 100871, China. Tel.: +86 10 82529066; fax: +86 10 82529010.
E-mail addresses: chenlinpku06@163.com (L. Chen), zhxrduph@yahoo.com (X.-R. Zhang).
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Nomenclature

A	area (m^2)
CCS	carbon capture and sequestration
COP_{LPC}	coefficient of performance, the ratio of cooling capacity in LPC to compressor work in LPC
COP_{SL}	coefficient of performance, the ratio of cooling capacity in LPC to all the compressor works
d	diameter (m); gap width (m)
E^*	activation energy (J)
FET	freeze-etch technique
H	height (m)
J	vaporation/sublimation rate (mol cm^{-2} s^{-2})
k	rate constant for vaporation/sublimation (s^{-1}); Boltzmann constant (J K^{-1})
L	length (m)
LES	large eddy simulation
Nu	Nusselt number
P	pressure (MPa)
Pr	Prandtl number
Q	heat flux input (W m^{-2})
R	universal gas constant (J mol^{-1} K^{-1}); radius (m)
t	temperature (K)
T	temperature (°C)
u	velocity (m s^{-1})
VR	volume ratio
W_h	compressor work in the high-pressure cycle (kW)
W_l	compressor work in the low-pressure cycle (kW)
x	horizontal length (m)
z	vertical length (m)
Δh_{lcool}	cooling capacity in the low-pressure cycle (kJ kg^{-1})
Δh_{lc1}, Δh_{lc2}	heat exchanging quantities in the condenser of hot water, and the condenser of cool water, in the low-pressure cycle, respectively (kJ kg^{-1})
Δh_{lc1}, Δh_{lc2}	heat exchanging quantities in the gas cooler of hot water, and the gas cooler of cool water, in the high-pressure system, respectively (kJ kg^{-1})

Greek symbols

α	ratio coefficient
δ	boundary thickness (m)
ξ	non-dimensional vertical direction
η	non-dimensional radial direction
θ	angle (degree)
φ	angle (rad)

Subscripts

0	reference value
cr	critical point
eq	equilibrium state
exp	experimental value
i	interface value
l	liquid phase
max	max value
p	particle
s	static state
ther	theoretical value
tr	triple point
v	vaporation; vapor phase
w	wall value

1. Introduction

In recent years, sublimation flow and heat transfer have been proposed and utilized in real applications. Compared with traditional vapor-compression thermodynamic refrigeration cycles, using solid–gas sublimation flow can achieve more stable operation and probably higher heat recovery capacity, due to the relative high latent heat of sublimation process. Therefore recently the investigation of solid–gas sublimation flows and its related application system designs has attracted a lot of research groups and engineer from both scientific world and industrial sectors (Robertson, 1932; Nelson, 1942; Lester and Somorjai, 1968; Eisenbraun et al., 1995; Michaelides and Lasek, 1987).

Indeed, sublimation is one of the phase change mechanisms happening everyday in the world. As shown in Fig. 1 (Aoki et al., 2002), dry ice sublimation is shown specifically for two different states when immersed in liquid tank. Early studies around 1930s have begun to investigate the basic thermo-physical nature of application (Robertson, 1932; Nelson, 1942). At that stage, the main topics were set around the sublimation rate from the viewpoint of chemical reaction/engineering or chemical physics. Later, more groups studied thermal equilibrium and near-equilibrium sublimation process, which may assume the ideal condition of vacuum sublimation in order to obtain reasonable results with experiments. As the sublimation substances such as iodine, naphthalene and camphor were more and more used in domestic and engineering fields, more studies came out since 1970s (Somorjai, 1968; Davy and Branton, 1970). However, the sublimation mechanism and physics behind what is seen are still not fully revealed. At the same time, more studies focused on the different factors that affect the sublimation rate of a crystal or particle, where the structural and chemical arrangements are analyzed from surface vaporizing to sublimation. Many groups have reported theoretical and experimental results measured for atomic crystal, molecular crystal, ionic crystal and others, under congruent or non-congruent sublimation process (Lester and Somorjai, 1968). Till recent years, there were still studies based on this general understanding of sublimation physics and the main focus on theoretical analysis and methods of numerical developments could be found (Schinzer and Kinzel, 1998; Smilauer and Vvedensky, 1995; Zhu et al., 2007; Krishnamurthy et al., 1990; Latyshev et al., 1996). The current review study will focus on the basic historic development of sublimation field and related cryogenic/refrigeration oriented applications in recent years.

However, the majority of those theories and experiments are based on strict assumptions of crystal structure and surface vaporization/sublimation laws (Somorjai and Lester, 1967). Large deviations are found between experiments and

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