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Research Paper

# Enhancing the convective heat transfer in liquid oxygen using alternating magnetic fields

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## HIGHLIGHTS

- Magnetic field actuated heat transfer of liquid oxygen was studied numerically.
- The vortex generation and shedding improved the heat transfer significantly.
- The maximum increment in heat transfer at $Re = 500$ and 0.5 T was 86.1%.
- The proposed method had the advantage of low additional pressure drops.

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ABSTRACT

Compact heat exchangers working with liquid oxygen play a major role in the cryogenic air separation units. In this paper a novel alternating magnetic field actuated method, utilizing the paramagnetic property of oxygen, was proposed for enhancing the convective heat transfer in this kind of heat exchangers. A modeling investigation based on a rectangular channel with the proposed enhancement method was conducted by two-dimensional finite-element simulation. The effects of background magnetic field, inlet flow condition, and cascade configuration on the heat transfer were numerically analyzed. The numerical results indicated that vortices were generated and shed due to the periodically changing magnetic force. The vortex shedding caused fluctuation of the thermal boundary layer and mixing of cold and hot fluids, which significantly improved the heat transfer. At $Re = 500$ and $B_0 = 0.5$ T, an increase of 86.1% in the overall Nusselt number was observed with a single steel bar, compared with the free-flow case without any enhancement. The proposed magnetic field actuated enhancement method provides a great potential for improving the heat transfer performance in liquid oxygen without leading to large pressure drops.


## 1. Introduction

Cryogenic air distillation is widely used to produce oxygen economically and massively in order to satisfy the huge demands of the metallurgical and chemical industries. Currently, the maximum capacity of an air separation unit (ASU) is 120,000 $Nm^3 \cdot h^{-1}$ (oxygen), with a specific power consumption of 0.38 $kWh \cdot m^{-3}$ [1]. Increasing the efficiency and minimizing the equipment size become the main factors in further improving the capacity of ASUs.

Compact heat exchangers play a major role in ASUs. The external energy provided to reach very low temperatures required for distillation process must be recovered through an efficient heat exchanger to arrive at an economical process [2]. Recently, numerous efforts have been made to enhance the heat transfer of compact heat exchangers. Transverse disturbed structures such as fins, ribs, cavities, and cylinders have been widely studied. Kelkar and Patankar [3] analyzed the heat transfer inside the parallel-plate channel with staggered fins. The fins were found to cause the flow to deflect significantly and impinge upon the opposite wall so as to increase the heat transfer coefficient. Pourgholam et al. [4] studied the effects of rotating and oscillating blades on the forced convection heat transfer numerically. The maximum Nusselt number at $Re = 50$ increased by 32.4% with the oscillating blades. These disturbed structures interrupt the boundary layer and enhance the heat transfer. However, there are drawbacks to these approaches. The achieved heat transfer enhancement is always accompanied with high pressure drops. Moreover, in the high velocity and near-critical situations, contact between the disturbed structures and the heat transfer medium probably causes fatigue deformation, stress concentration, and cavitation erosion.

Non-contact enhancement technology is promising to obtain higher heat transfer coefficient with low pressure drop and reasonable equipment strength. As the main working fluid of heat exchangers in ASUs, oxygen is a kind of paramagnetic substances that has a relatively high magnetic susceptibility ($\chi = 3.45 \times 10^{-3}$ at 90 K). This unique property of oxygen has long been employed to

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measure the concentration of oxygen, improve combustion, and produce oxygen-enriched air [5–8]. In this study, a novel non-contact method is proposed by the present authors for enhancing the convective heat transfer in liquid oxygen by introducing an alternating magnetic field [9]. Our hypothesis was that the combination of magnetic field and cryogenic heat transfer may offer additional benefits such as, strengthening of the paramagnetic property according to Curie law, and precise magnetic control of the flow in cryogenic areas. Quantitative understanding of the mechanism involved in this process is required for the design, optimization, and finally fabrication of this kind of heat exchangers. Therefore, a modeling investigation of the proposed enhancement method was conducted.

## 2. Problem definition and numerical model

As shown in Fig. 1a, a plate-fin heat transfer unit in ASU typically consists of fins, parting sheets, and side bars. The fins and parting sheets divide the flow area into a number of narrow rectangular channels.

A single rectangular channel was simplified to a 2-dimentional numerical model at plane A, as shown in Fig. 1b. The whole channel was assumed to be placed into a uniform background magnetic field obtained by a coil surrounding the whole heat exchanger. Silicon steel 50PN470 bars were placed close to the channel walls at the outside. Silicon steel, a soft magnetic material, has high magnetic permeability and low coercive force. Due to the background field, high gradient magnetic regions were formed close to the surface of the bars. When the background field was turned off, the magnetism of the bars disappeared immediately because of their low coercive force.

Liquid oxygen flowed through the parallel-plate channel from left to right. A finite-element model was developed to predict the heat transfer under the magnetic field. The model was based on the Maxwell's equations for solving the magnetic field in the flow channel, the Navier–Stokes equation for solving the laminar flow of the incompressible liquid oxygen, and the energy equation for solving the convective heat transfer between the isothermal channel walls and the passing cryogenic fluid.

### 2.1. Magnetic equations

The magnetic fields were governed by Maxwell's equations:

$$\nabla \times \boldsymbol{H} = 0 \tag{1}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{2}$$

The constitutive relation between $\boldsymbol{B}$ and $\boldsymbol{H}$ in the fluid satisfied:

$$\boldsymbol{B} = \mu_0 \mu_r \boldsymbol{H} \tag{3}$$

Silicon steel 50PN470 was treated as a nonlinear magnetic material. Its constitutive relation was given by a material properties database supplied by Precision Wafers Inc. [10]. The magnetic vector potential $\boldsymbol{A}$ was defined by:

$$\nabla \times \boldsymbol{A} = \boldsymbol{B} \tag{4}$$

$$\nabla \cdot \boldsymbol{A} = 0 \tag{5}$$

For a 2D simulation, the magnetic vector potential was assumed to have a nonzero component only perpendicular to the computational domain. The background fields were switched on and off periodically according to a step function, and the sharp corners were smoothed within one fifth of a period. The high level of the step function corresponded to the background magnetic flux density, while the low level was set to zero.

An infinite-element boundary condition was applied to the area surrounding the computational domain. All interior boundaries were assumed to be continuous.

### 2.2. Fluid flow equation

Assuming liquid oxygen to be incompressible ($\nabla \cdot \boldsymbol{u} = 0$), the governing equation of the fluid flow can be expressed using the Navier–Stokes equation:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla p + \mu \nabla^2 \boldsymbol{u} + \boldsymbol{F} \tag{6}$$

where $\boldsymbol{F}$ is the volume force, which corresponds to the magnetic force exerted on the paramagnetic oxygen:

$$\boldsymbol{F} = \frac{1}{2\mu_0} \chi \nabla \boldsymbol{B}^2 \tag{7}$$

The susceptibility of oxygen $\chi$ was obtained from the experimental molar magnetic susceptibility (change over temperature) [11].

The Reynolds number was defined by:

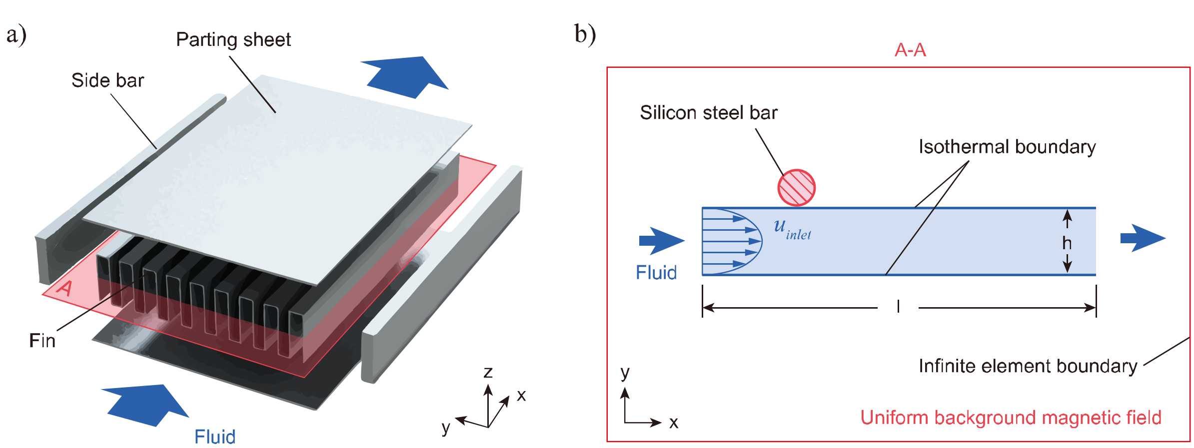


**Fig. 1.** Schematic of magnetic field actuated enhancement method: (a) three-dimensional conceptual representation of a plate-fin heat transfer unit, (b) two-dimensional simplified model used in the finite-element simulation.