Bio-inspired Self-agitator for Convective Heat Transfer Enhancement

Zheng Li[1, b)], Xianchen Xu[1, b)], Kuojiang Li[1, b)], Yangyang Chen[1], Zhaoqing Ke[1], Sheng Wang[1], Hsiu-Hung Chen[1], Guoliang Huang[1, a)], Chung-lung Chen[1, a)], Chien-Hua Chen[2]

[1]*Mechanical and Aerospace Engineering, University of Missouri-Columbia, Columbia, Missouri, 65201, USA*

[2]*Advanced Cooling Technologies, Inc. Lancaster, Pennsylvania 17601, USA*

Convective heat transfer plays an important role in both fundamental research and the development of high-performance heat exchangers. Inspired by blades of grass vibrating in the wind, we developed a self-agitator for convective heat transfer enhancement. Because of fluid-structure interactions, the agitator, with self-sustained vibration, can generate strong vortices to significantly break the thermal boundary layer and improve fluid mixing for enhanced convective heat transfer. In particular, we establish a methodology to link the vorticity field at a preferred frequency to the optimal improvement in the convective heat transfer. To identify the self-agitator preferred frequency, mode analysis is performed with simulation results using dynamic mode decomposition. Experimental results are also obtained to further validate the proposed approach. These results show that the proposed self-agitator design can improve the convective heat transfer by 120% in a conventional heat exchanger without additional pumping power requirements and can achieve a Nusselt number of up to 30 within the laminar flow region, which is improved by 200% with the same Reynolds number compared with the clean channel.

[a)] **Authors to whom correspondence should be addressed. Electronic addresses: ChenCL@Missouri.edu Tel: 001-573-882-9037 and** HuangG@Missouri.edu

[b)] **Authors contributed equally to this work**

1. Introduction

As the need for highly efficient convective heat transfer rates for electronic component cooling and power generation continues to grow, bio-inspired vortex generation with fluid-structure interaction (FSI)[1]–[7] has been highlighted as a promising method to improve the overall convective heat transfer without additional pumping power requirements. It is based on the notion that ages of biological evolution could provide effective inspiration for the design of useful technologies. Examples of FSI in nature, such as grass vibrating in wind or birds flying, show that the FSI process can generate fluid vortices which can be used to improve fluid mixing. Therefore, bio-inspired designs can be developed to improve convective heat transfer based on the enhanced mixing processes. Two categories of FSI exist and the driving force of structural vibration distinguishes them; an active one with external power and a passive one without external power requirement. Active FSI vortex generators have been employed to enhance heat transfer in various applications [8]–[11]. These can be applied to current heat exchangers where their oscillating frequencies directly affect the thermal performance. However, they require an additional power supply system to drive the structural oscillation, limiting the range of practical applications. Passive FSI vortex generators for heat transfer enhancement [12]–[16] have also been investigated. However, a method to improve the vortex field has not yet been identified. This article focuses on passive methods where we develop a bio-inspired self-agitator for convective heat transfer enhancement and explore the principles underlying its performance.

Currently, a range of methods exist for achieving convective heat transfer enhancement, such as offset strip fins, T-mixers, Dean flow in curved pipes and stationary vortex generators. In general, they all create vortices to enhance mixing for convective heat transfer enhancement. For various designs, transverse or longitudinal vortices can be generated for heat transfer enhancement [17]–

[28]. Compared with a stationary vortex generator, the FSI process has been shown to achieve better performance [29]. Thermal performance is maximized when large modulations are created at the boundary layer of the heat transfer surface while avoiding the creation of strong vortices in other regions [30]. Though many methods exist to introduce vortices for heat transfer enhancement, what type of vortices provides the best performance is still unclear.

In this work, we first investigate the fundamental relation between vorticity modes and thermal performance. To explore this, dynamic mode decomposition (DMD) [31]–[33] is performed with the transient numerical results in the vorticity field. Subsequently, various modes with fixed frequencies can be achieved. Then the vorticity modes introduced by the structural motions can be distinguished by matching the frequency of the vorticity mode to that of the structural motion. Several other modes (including the dominant one) exist concurrently with frequencies different from that of the structural motion. Another interesting phenomenon is that the first and second fluid modes' frequencies do not change significantly for different self-agitator conditions for a specific geometry for heat transfer. This indicates that the heat exchanger has its "preferred" frequencies for the vorticity field in convective heat transfer enhancement. It is well accepted that vortices near the boundary with different frequencies can break the thermal boundary layer to improve convective heat transfer. However, no direct guidance has been achieved before to reveal how to refine the vorticity field for further improving convective heat transfer. From the analysis part of this work, we find that synchronizing the preferred frequency to the structural motion can improve convective heat transfer. This conclusion is used to guide the experimental structural design, and the experimental results demonstrate that the self-agitator can improve the thermal performance significantly. We choose a commercially available plate fin heat exchanger (6.6mm gap, 22.0mm height, and 120.0mm length.) as an example to test the self-agitator performance.

The experimental results demonstrate that heat transfer can be enhanced by 120% without additional pumping power requirements compared with the clean channel while achieving a Nusselt number of up to 30 within the laminar flow region by matching to the preferred frequency.

2. Results

Test structure and measurements.

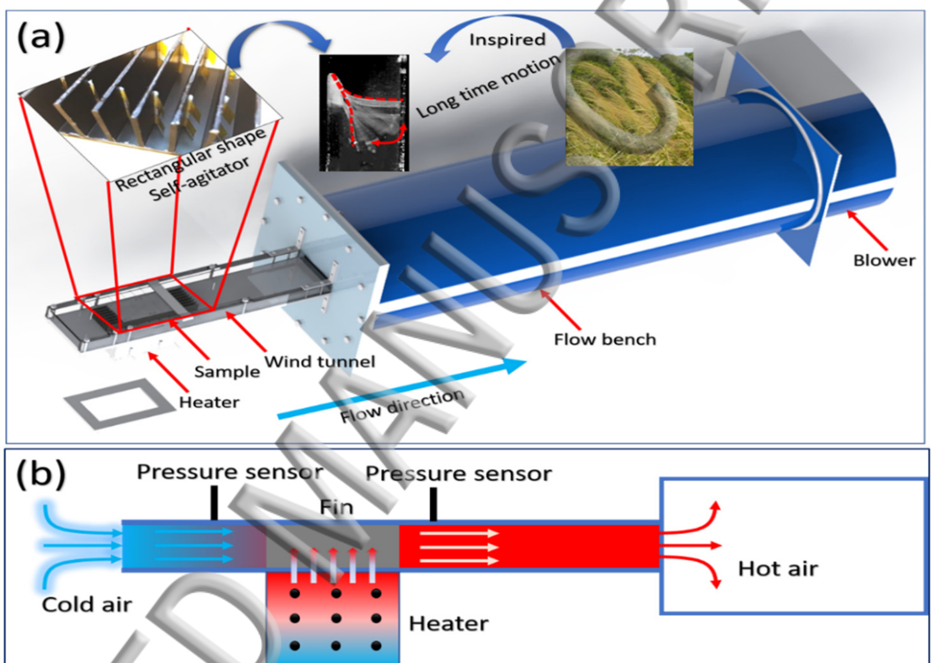


Figure 1. Experimental setups: 150 CFM Chamber, Airflow Measurement Systems is employed to provide cooling air. Details for the experiment setups can be found in our previous works[34]–[37] and Supplementary Material.

Inspired by biological processes observed in nature, a self-agitator design is proposed where a thin-film material is attached to a heat exchanger with a specially designed shape as shown in Figure 1. As airflow is introduced, FSI causes the structure to vibrate, generating vortices that will improve the overall heat transfer rates in the channels of the heat sink. The enhanced heat sink performance with self-agitators is measured in terms of increased rejected heat over a range of flow rates compared to the baseline flow in the absence of the self-agitators.

Dynamics of self-agitator.

To guide the prototype design, numerical investigations are performed to study the dynamics of the self-agitator. Verification of the numerical tools for solving fluid structure interaction and heat transfer problems has been reported in our recent papers [29], [34].

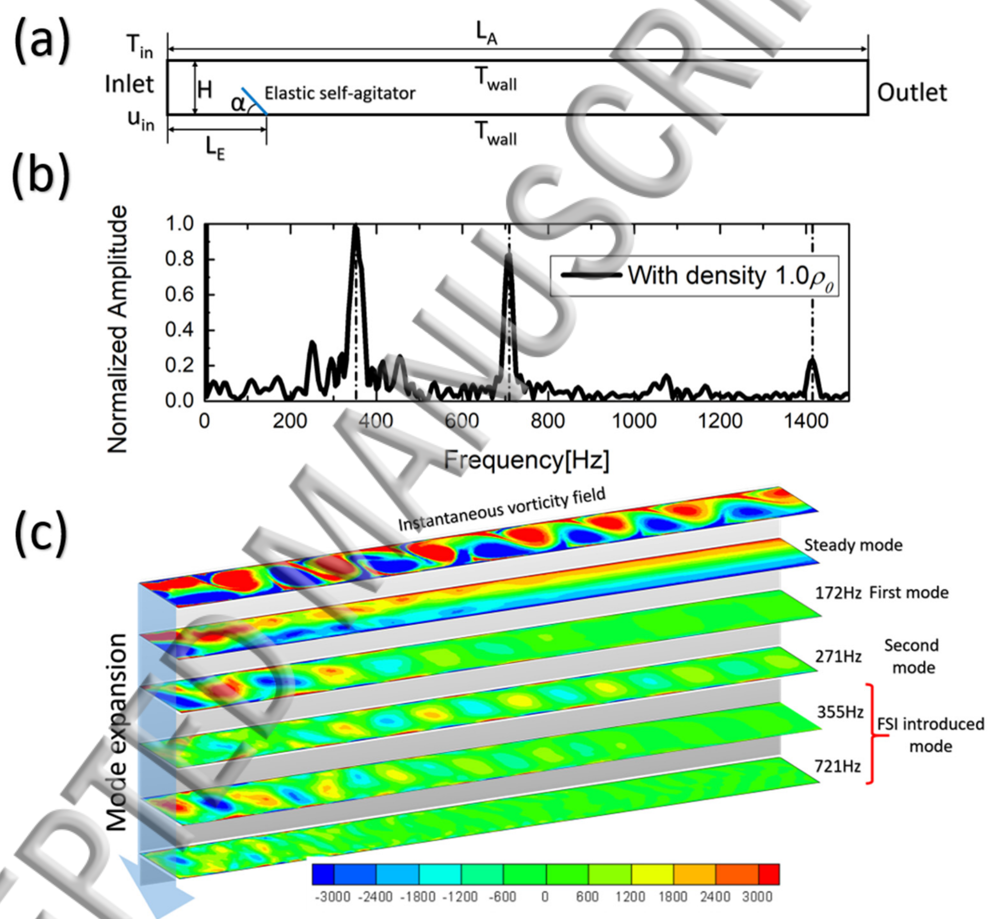


Figure 2. Numerical results and modal analysis: (a) 2-D assumption is applied to simplify the FSI process of the self-agitator; (b) To evaluate the structural oscillation frequency, Fourier analysis is performed on the maximum displacement of the self-agitator; (c) A series of snapshots of the transient vorticity fields are used for DMD analysis. Only the first few low-frequency modes are included here.

First, numerical simulations are performed with the same geometry as the experimental setups: the height and length of the channel is 6.6 mm and 120 mm, respectively. The initial inclined angle α of self-agitator is 45°, which is motivated by other groups' results [38]. The Young's Modulus of the self agitator is 2.5 GPa and the density (ρ_0) is 1420 kg/m^3; these properties are obtained from commercially available Kapton film. The inlet velocity is 4 m/s and the temperatures T_{wall} and T_{in} are 308 K and 298 K, respectively.

This FSI problem is solved numerically and the Fourier analysis for the structural motion is shown in Fig 2 (b). Transient results of vorticity fields are employed to perform the modal analysis with DMD. The two dominant frequencies are found to be 352 Hz and 704 Hz. Fig. 2(c) shows one snapshot of the vorticity fields in the region downstream of the surface agitator and the corresponding modes obtained from modal analysis. A vortex street exists through the channel as shown with instantaneous vorticity contours and it can be decomposed into various modes with DMD while each mode has impact in the whole channel. In our previous work [29], it has been demonstrated that the thermal performance relates to the steady modes (not time dependent) directly. However, no efforts have been made to refine the steady mode for better thermal performance. In this article, we explore to create resonance between flow and structure modes to improve the thermal performance. Besides the steady mode, the first and second unsteady modes (172 Hz and 271 Hz) play the important roles in the vorticity field and their frequencies are different from the structure ones. These can be the targeted frequencies to resonate with the structure for obtaining heat transfer enhancement. The third and fourth modes (355 Hz and 721 Hz) have frequencies similar to the structural motions. Therefore, they could be introduced by the motion of the structure. Assuming the dominant flow modes do not change in different FSI processes, we need to decrease the structural resonance frequencies by 24% to reach 271 Hz or by

51% to meet 172 Hz, so that the structure can resonate with the dominant flow modes.

Modal analysis and preferred frequency.

To decrease the structure's resonant frequency, eigenfrequencies of the self-agitator are analyzed for different structure densities as shown in Figure 3(a), where the original density, ρ_0, for the structure is 1420 kg/m^3. The eigenfrequency of the original density self-agitator is 300 Hz, which is very close to the condition found in the FSI process. Therefore, the eigenfrequencies for different densities can provide guidance for obtaining the final structure's resonant frequency in FSI process. As shown in Fig. 3, multiplication factors of 1.7 and 4.0 times the original density can decrease the resonant frequencies by 24% and 51%, respectively, to achieve a structural resonance with dominant flow modes in FSI.

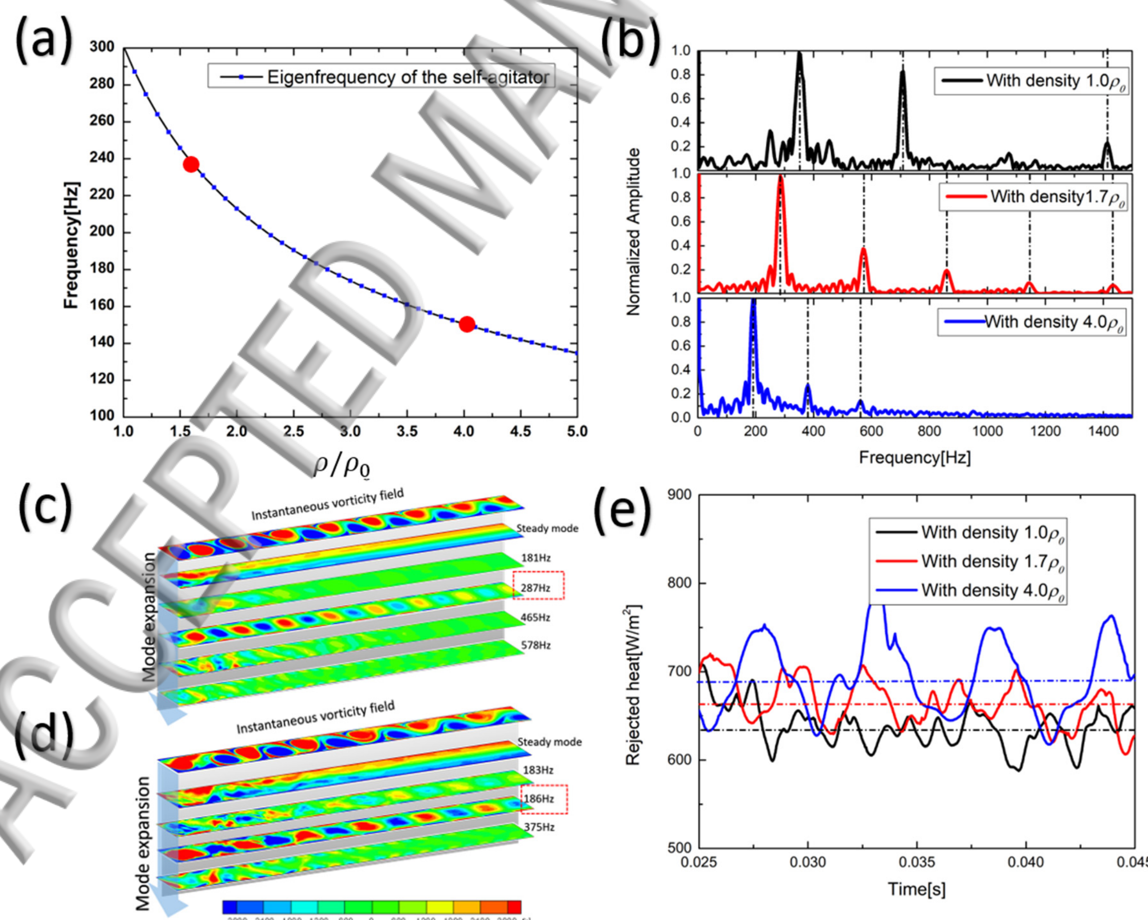


Figure 3. Results comparison for different densities. (a) Eigenfrequencies changing with density are performed for self-agitator with time averaged shape in FSI simulation; (b) Fourier analysis for different density self-agitators. The results show that with designed densities, the desired frequencies are achieved; (c) DMD results for 1.7ρ_0 condition, the mode with 287Hz is enhanced; (d) DMD results for 4.0ρ_0 condition, the mode with 186Hz is enhanced; (e) With the designed densities, the thermal performance can be improved comparing with the original one.

Two FSI cases are solved numerically with 1.7ρ_0 and 4.0ρ_0 while the other parameters are the same as the original density case. Fourier analysis of the structural motions are shown in Fig. 3 (b), where it is shown that a higher density results in a lower resonant frequency. The multiplication factors of 1.7ρ_0 and 4.0ρ_0 can decrease the structure frequency by 23% and 49% compared to the original density condition, which fulfills the goals set in last section. Fig. 3(c) shows one snapshot of the vorticity fields in the region downstream of the surface agitator and the corresponding modes from modal analysis for the 1.7ρ_0 condition. Besides the steady mode, the first and second unsteady modes (181 Hz and 287 Hz) play the dominant roles in the flow fields. The second mode is enhanced because its frequency is close to the resonant frequency of the structure. Therefore, with the refined 1.7ρ_0, the specific mode is enhanced as we expected. Fig. 3(d) shows one snapshot of the vorticity field in the region downstream of the self-agitator and the corresponding modes from modal analysis for the 4.0ρ_0 condition. The dominant unsteady modes have frequencies of 183 Hz and 186 Hz. The flow mode at 186 Hz is enhanced significantly as previously expected. Therefore, enhancing the targeted mode by adjusting the structure's density is promising. After adjusting the structure design, the results are shown in Fig. 3(c) and (d). In contrast to the original design in Fig. 2(c), the enhanced modes (highlighted in Fig. 3(c) and (d)) show better vorticity preservation through the channel, even though the vortices still decay in the streamwise direction. To evaluate the performance of the refined self-agitators, rejected heat rates are compared for the different conditions as shown in Fig. 3(e). For the original density condition, the averaged rejected heat is 634 W/m^2 with 198 Pa of pressure loss. For the 1.7ρ_0 case, the average rejected heat is increased to 687 W/m^2 and the pressure loss is decreased to 175 Pa. With 4.0ρ_0, the average rejected heat increases to 698 W/m^2 while the pressure loss changes to 203 Pa. Compared with the original density condition, heat transfer performance is improved with self-agitators of redefined density. These results agree well with our previous work[29] by comparing the steady modes in different cases in Figures 2 and 3. In the highest-performance case, the steady mode of vorticity has the most discrete patterns compared to the steady mode in the other cases, which indicates more effective breaking of the thermal boundary layer. Therefore, matching the structural resonant frequencies with the first few dominant flow modes can improve the thermal performance of the self-agitator. First dominant mode frequencies are preferred for convective heat transfer enhancement. Currently, the frequencies of the first dominant modes for different density conditions are quite close to each other (about 180 Hz). Therefore, one existing heat exchanger with a given geometry has its preferred frequency of vorticity field. These results can guide the future design of self-agitators.

Self-agitator motion and thermal performance.

As we previously discussed, the designed heatsink with certain channel gap has a preferred frequency from the 2-D study and it is reasonable to hypothesize that a 3-D case has similar behavior. To validate the performance of the optimized self-agitator with the preferred frequency, we designed a rectangular self-agitator using 0.025 mm thickness Kapton film. Here the resonant frequency of Kapton film based self-agitator is designed to be close to the predicted channel preferred frequency in the simulation (about 180 Hz). To investigate the vibration characteristics of the self-agitator in the channel we use a high-speed camera to monitor the motion of the self-agitator as shown in Fig.1 (experimental setup), which has been built and verified in our lab[34]–[37]. As the channel height is 21.8mm, we placed two rectangular self-agitators as a pair to generate stronger vortices. The vibration characteristics of the designed self-agitators are shown in Fig. 4 (a), while the results show that the self-agitator near the top and near bottom vibrate with the same frequency but in different phases. Fig. 4 (b) (Multimedia view) shows the motion for rectangular shape self-agitator; the slow motion results indicate that the two self-agitators in one row have the out of phase phenomenon[39]–[41], which can reduce the pressure drop of the self-agitator.

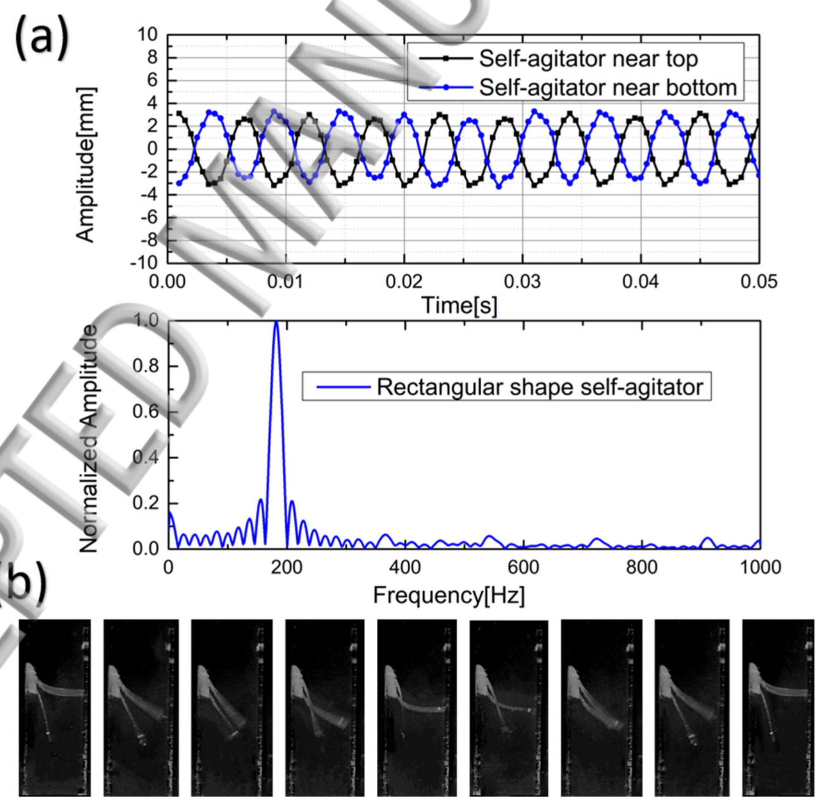


Figure 4. Self-agitator motions. (a) Two self-agitators are set in one row and they are moving out-of-phase. Fourier analysis is performed with vibration amplitude. (b) (Multimedia view) Out-of-phase motions of self-agitators in one period are presented.

The thermal tests were conducted for clean channel, rectangular shaped self-agitators and a rigid longitudinal vortex generator (LVG), which can be viewed as state of the art[17], [19], [23], [27], [28], [30], [42]–[46], to evaluate the thermal performance. As shown in Fig. 5, under the same conditions, the overall Nusselt number for the self-agitators is significantly higher than those with the LVGs and clean channel cases. The Nusselt number (Nu) and Reynolds number (Re) are widely used to evaluate the performance of convective heat transfer [29]. As shown in Fig. 5 (a), the self-agitator can improve the Nu by 200% at the same Re. Fig. 5(b) shows that the self-agitator can enhance the heat transfer coefficient by 120% at the same pumping power compared with the clean channel. The experimental results above indicate that the thin-film based self-agitator can obtain better heat transfer performance than the LVG, which also proves that a self-agitator oscillating at the channel's preferred frequency can enhance the heat transfer performance of the heatsink.

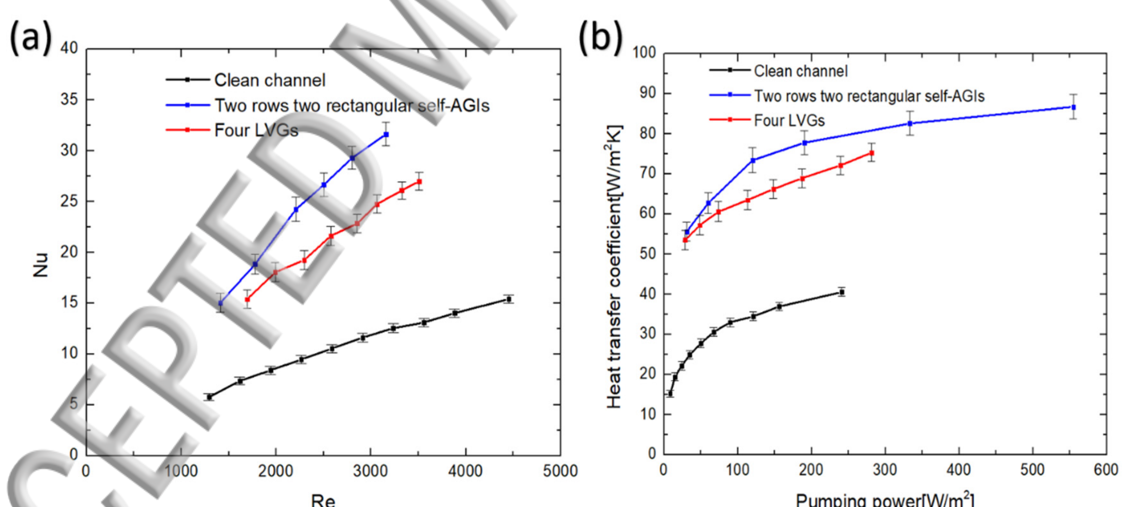


Figure 5. Results comparison. (a) Nu-Re, Two row of self-agitator can achieve better performance of four rows of LVGs. (b) Pumping power is calculated with pressure loss multiply velocity.

3. Discussions

This article includes a self-agitator design to improve convective heat transfer and explores the fundamental relationship between heat transfer and vorticity field, which has never been discussed before. From modal analysis of the transient vorticity fields, the dominant modes and modes introduced by the self-agitator motions can be distinguished. Matching the frequency of structural motion to the dominant mode can create resonance to enhance the fluid mixing. These findings show that the FSI process of the self-agitator can improve the convective heat transfer significantly and that further enhancement can be achieved by approaching the preferred frequency of the vorticity field. The self-agitators were fabricated and experimentally tested for convective heat transfer enhancement. Self-agitator oscillation at the preferred frequency is achieved and experimental results demonstrate that the heat transfer can be enhanced by 120% without additional pumping power requirements while the Nusselt number can be improved by 200% with the same Reynolds number compared with the clean channel.

SUPPLEMENTARY MATERIAL

See supplementary material for the detailed information for the experimental measurement system for the thermal performance test and numerical method in the paper.

4. Acknowledgments

The authors greatly appreciate the support of ARPA-E under Grant No. DE-AR0000582. The authors would like to acknowledge Alex Chen and Miles V. Barnhart for their constructive comments.

5. Author's contribution

Z. L. and Y. Y. C. contributed to the simulation part. Z. L. performed the modal analysis for optimal design. X. X. and K. J. L. fabricated the prototype and carried on the experiment test. Z. Q. K., S. W. and H. H. C. discussed the results and commented on the manuscript. G. L. H., C. L. C. and C. H. C. conceived and guided the project. All authors wrote the manuscript.

6. References

[1] H. Weimerskirch, J. Martin, Y. Clerquin, P. Alexandre, and S. Jiraskova, "Energy saving in flight information," *Nature*, vol. 413, pp. 697–698, 2001.

[2] S. J. Portugal, T. Y. Hubel, J. Fritz, S. Heese, D. Trobe, B. Voelkl, S. Hailes, A. M. Wilson, and J. R. Usherwood, "Upwash exploitation and downwash avoidance by flap phasing in ibis formation flight," *Nature*, vol. 505, no. 7483, pp. 399–402, 2014.

[3] I. Khan, N. A. Shah, and L. C. C. Dennis, "A scientific report on heat transfer analysis in mixed convection flow of Maxwell fluid over an oscillating vertical plate," *Sci. Rep.*, vol. 7, no. September 2016, p. 40147, 2017.

[4] J. Bae, J. Lee, S. Kim, J. Ha, B. S. Lee, Y. Park, C. Choong, J. B. Kim, Z. L. Wang, H. Y. Kim, J. J. Park, and U. I. Chung, "Flutter-driven triboelectrification for harvesting wind energy," *Nat. Commun.*, vol. 5, pp. 1–9, 2014.

[5] A. D. Becker, H. Masoud, J. W. Newbolt, M. Shelley, and L. Ristroph, "Hydrodynamic schooling of flapping swimmers," *Nat. Commun.*, vol. 6, no. May, p. 8514, 2015.

[6] J. Zhang, S. Childress, A. Libchaber, and M. Shelley, "Flexible filaments in a flowing soap film as a model for one-dimensional flags in a two-dimensional wind," *Nature*, vol. 408, no. 6814, pp. 835–839, Dec. 2000.

[7] R. K. B. Gallegos and R. N. Sharma, “Flags as vortex generators for heat transfer enhancement: Gaps and challenges,” *Renew. Sustain. Energy Rev.*, vol. 76, no. March, pp. 950–962, 2017.

[8] W. S. Fu and B. H. Tong, “Numerical investigation of heat transfer characteristics of the heated blocks in the channel with a transversely oscillating cylinder,” *Int. J. Heat Mass Transf.*, vol. 47, no. 2, pp. 341–351, 2004.

[9] A. Beskok, M. Raisee, B. Celik, B. Yagiz, and M. Cheraghi, “Heat transfer enhancement in a straight channel via a rotationally oscillating adiabatic cylinder,” *Int. J. Therm. Sci.*, vol. 58, pp. 61–69, 2012.

[10] B. Celik, M. Raisee, and A. Beskok, “Heat transfer enhancement in a slot channel via a transversely oscillating adiabatic circular cylinder,” *Int. J. Heat Mass Transf.*, vol. 53, no. 4, pp. 626–634, 2010.

[11] M. Pourgholam, E. Izadpanah, R. Motamedi, and S. E. Habibi, “Convective heat transfer enhancement in a parallel plate channel by means of rotating or oscillating blade in the angular direction,” *Appl. Therm. Eng.*, vol. 78, pp. 248–257, 2015.

[12] F. Herrault, P. A. Hidalgo, C. H. Ji, A. Glezer, and M. G. Allen, “Cooling performance of micromachined self-oscillating reed actuators in heat transfer channels with integrated diagnostics,” *Proc. IEEE Int. Conf. Micro Electro Mech. Syst.*, no. February, pp. 1217–1220, 2012.

[13] K. Kota, P. Hidalgo, Y. Joshi, and A. Glezer, “Hybrid liquid immersion and synthetic jet heat sink for cooling 3-D stacked electronics,” *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 2, no. 5, pp. 817–824, 2012.

[14] P. Hidalgo and A. Glezer, “Direct actuation of small-scale motions for enhanced heat

transfer in heated channels," *Annu. IEEE Semicond. Therm. Meas. Manag. Symp.*, pp. 17–23, 2014.

[15] P. Hidalgo, S. Jha, and A. Glezer, "Enhanced Heat Transfer in Air Cooled Heat Sinks Using Aeroelastically Fluttering Reeds Reed Motion and Flow Characterization," vol. 2015, no. October, 2015.

[16] J. Shi, J. Hu, S. R. Schafer, and C.-L. (C. L. . Chen, "Numerical study of heat transfer enhancement of channel via vortex-induced vibration," *Appl. Therm. Eng.*, vol. 70, no. 1, pp. 838–845, 2014.

[17] C. Min, C. Qi, X. Kong, and J. Dong, "Experimental study of rectangular channel with modified rectangular longitudinal vortex generators," *Int. J. Heat Mass Transf.*, vol. 53, no. 15–16, pp. 3023–3029, 2010.

[18] K. Yang, J. Jhong, Y. Lin, K. Chien, and C. Wang, "On the Heat Transfer Characteristics of Heat Sinks : With and Without Vortex Generators," vol. 33, no. 2, pp. 391–397, 2010.

[19] S. Caliskan, "Experimental investigation of heat transfer in a channel with new winglet-type vortex generators," *Int. J. Heat Mass Transf.*, vol. 78, pp. 604–614, 2014.

[20] M. J. Lawson and K. A. Thole, "Heat transfer augmentation along the tube wall of a louvered fin heat exchanger using practical delta winglets," *Int. J. Heat Mass Transf.*, vol. 51, no. 9–10, pp. 2346–2360, 2008.

[21] M. Oneissi, C. Habchi, S. Russeil, D. Bougeard, and T. Lemenand, "Novel design of delta winglet pair vortex generator for heat transfer enhancement," *Int. J. Therm. Sci.*, vol. 109, pp. 1–9, 2016.

[22] P. A. Sanders and K. A. Thole, "Effects of winglets to augment tube wall heat transfer in louvered fin heat exchangers," *Int. J. Heat Mass Transf.*, vol. 49, no. 21–22, pp. 4058–4069,

2006.

[23] J. M. Wu and W. Q. Tao, "Numerical study on laminar convection heat transfer in a rectangular channel with longitudinal vortex generator. Part A: Verification of field synergy principle," *Int. J. Heat Mass Transf.*, vol. 51, no. 5–6, pp. 1179–1191, 2008.

[24] M. Sheikholeslami, M. Gorji-Bandpy, and D. D. Ganji, "Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices," *Renew. Sustain. Energy Rev.*, vol. 49, pp. 444–469, 2015.

[25] S. Liu and M. Sakr, "A comprehensive review on passive heat transfer enhancements in pipe exchangers," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 64–81, 2013.

[26] K. Torii, K. M. Kwak, and K. Nishino, "Heat transfer enhancement accompanying pressure-loss reduction with winglet-type vortex generators for fin-tube heat exchangers," *Int. J. Heat Mass Transf.*, vol. 45, no. 18, pp. 3795–3801, 2002.

[27] J. M. Wu and W. Q. Tao, "Numerical study on laminar convection heat transfer in a channel with longitudinal vortex generator. Part B: Parametric study of major influence factors," *Int. J. Heat Mass Transf.*, vol. 51, no. 13–14, pp. 3683–3692, 2008.

[28] M. Fiebig, "Vortices, Generators and Heat Transfer," *Chem. Eng. Res. Des.*, vol. 76, no. 2, pp. 108–123, 1998.

[29] Z. Li, X. Xu, K. Li, Y. Chen, G. Huang, C. Chen, and C.-H. Chen, "A flapping vortex generator for heat transfer enhancement in a rectangular airside fin," *Int. J. Heat Mass Transf.*, vol. 118, pp. 1340–1356, 2018.

[30] K. Shoele and R. Mittal, "Computational study of flow-induced vibration of a reed in a channel and effect on convective heat transfer," *Phys. Fluids*, vol. 26, no. 12, 2014.

[31] P. J. SCHMID, "Dynamic mode decomposition of numerical and experimental data," *J.*

Fluid Mech., vol. 656, pp. 5–28, 2010.

[32] C. W. Rowley and S. T. M. Dawson, "Model Reduction for Flow Analysis and Control," *Annu. Rev. Fluid Mech.*, vol. 49, no. 1, pp. 387–417, 2017.

[33] C. W. ROWLEY, I. MEZIĆ, S. BAGHERI, P. SCHLATTER, and D. S. HENNINGSON, "Spectral analysis of nonlinear flows," *J. Fluid Mech.*, vol. 641, p. 115, 2009.

[34] Z. Li, X. Xu, K. Li, Y. Chen, G. Huang, C.-L. Chen, and C.-H. Chen, "Airfoil-shaped self-agitator for convective heat transfer enhancement," *Int. J. Therm. Sci.*, vol. 133, no. May, pp. 284–298, 2018.

[35] Z. Li, Y. Chen, X. Xu, K. Li, Z. Ke, K. Zhou, H. Chen, G. Huang, C. Chen, and C. Chen, "Air-Side Heat Transfer Enhancement With A Novel Self-Agitator," in *Proceedings of the ASME 2017 Heat Transfer Summer Conference*, 2017, p. HT2017-4971.

[36] Z. Li, Z. Ke, K. Li, X. Xu, Y. Chen, K. Zhou, H. Chen, G. Huang, and C. Chen, "NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON LONGITUDINAL VORTEX GENERATOR FOR HEAT TRANSFER ENHANCEMENT IN RECTANGULAR CHANNEL," in *Proceedings of the ASME 2017 Heat Transfer Summer Conference*, 2017, p. HT2017-4976.

[37] Z. Li, Y. Chen, X. Xu, K. Li, Z. Ke, K. Zhou, G. Huang, H.-H. Chen, C.-L. Chen, and C.-H. Chen, "A Novel Air Side Heat Transfer Enhancement Strategy with Self-Agitator," in *47th AIAA Fluid Dynamics Conference*, 2017.

[38] S. Ali, C. Habchi, S. Menanteau, T. Lemenand, and J. L. Harion, "Heat transfer and mixing enhancement by free elastic flaps oscillation," *Int. J. Heat Mass Transf.*, vol. 85, pp. 250–264, 2015.

[39] J. D. Hobeck and D. J. Inman, "Dual cantilever flutter: Experimentally validated lumped

parameter modeling and numerical characterization," *J. Fluids Struct.*, vol. 61, pp. 324–338, 2016.

[40] S. Majidi and A. Ahmadpour, "Thermally assisted restart of gelled pipelines: A weakly compressible numerical study," *Int. J. Heat Mass Transf.*, vol. 118, pp. 27–39, 2018.

[41] D. Li, Y. Wu, A. Da Ronch, and J. Xiang, "Energy harvesting by means of flow-induced vibrations on aerospace vehicles," *Prog. Aerosp. Sci.*, vol. 86, no. September, pp. 28–62, 2016.

[42] M. Laroussi, M. Djebbi, and M. Moussa, "Triggering vortex shedding for flow past circular cylinder by acting on initial conditions: A numerical study," *Comput. Fluids*, vol. 101, pp. 194–207, 2014.

[43] L. Léal, M. Miscevic, P. Lavieille, M. Amokrane, F. Pigache, F. Topin, B. Nogarède, and L. Tadrist, "An overview of heat transfer enhancement methods and new perspectives: Focus on active methods using electroactive materials," *Int. J. Heat Mass Transf.*, vol. 61, no. 1, pp. 505–524, 2013.

[44] H. Nassar, X. C. Xu, A. N. Norris, and G. L. Huang, "Modulated phononic crystals: Non-reciprocal wave propagation and Willis materials," *J. Mech. Phys. Solids*, vol. 101, pp. 10–29, 2017.

[45] X. Wang and S. Alben, "The dynamics of vortex streets in channels," *Phys. Fluids*, vol. 27, no. 7, 2015.

[46] P. H. Kao and R. J. Yang, "An investigation into curved and moving boundary treatments in the lattice Boltzmann method," *J. Comput. Phys.*, vol. 227, no. 11, pp. 5671–5690, 2008.

FIGURE CAPTIONS:

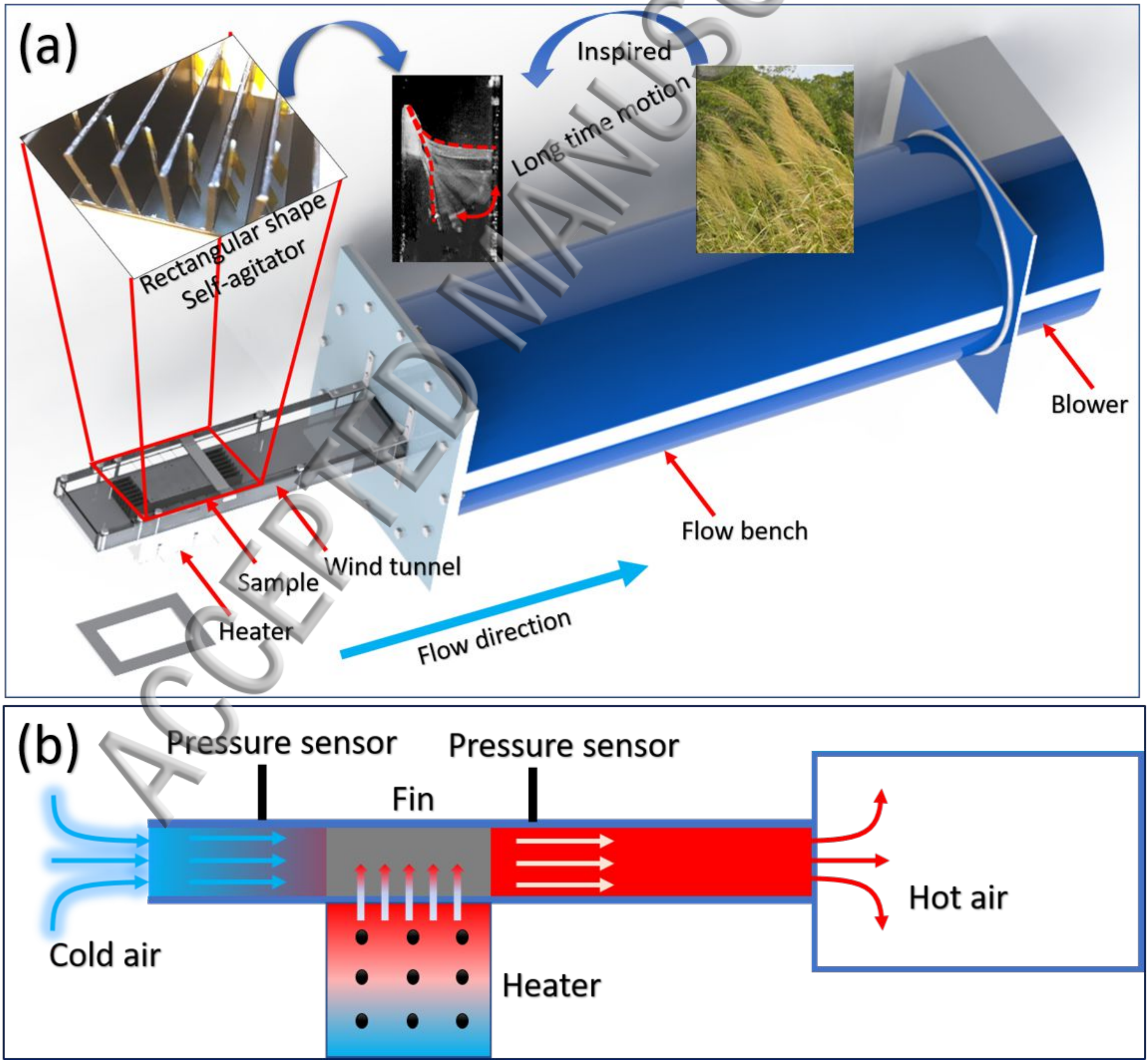
Figure 1. Experimental setups: 150 CFM Chamber, Airflow Measurement Systems is employed to provide cooling air. Details for the experiment setups can be found in our previous works[34]–[37] and Supplementary Material.

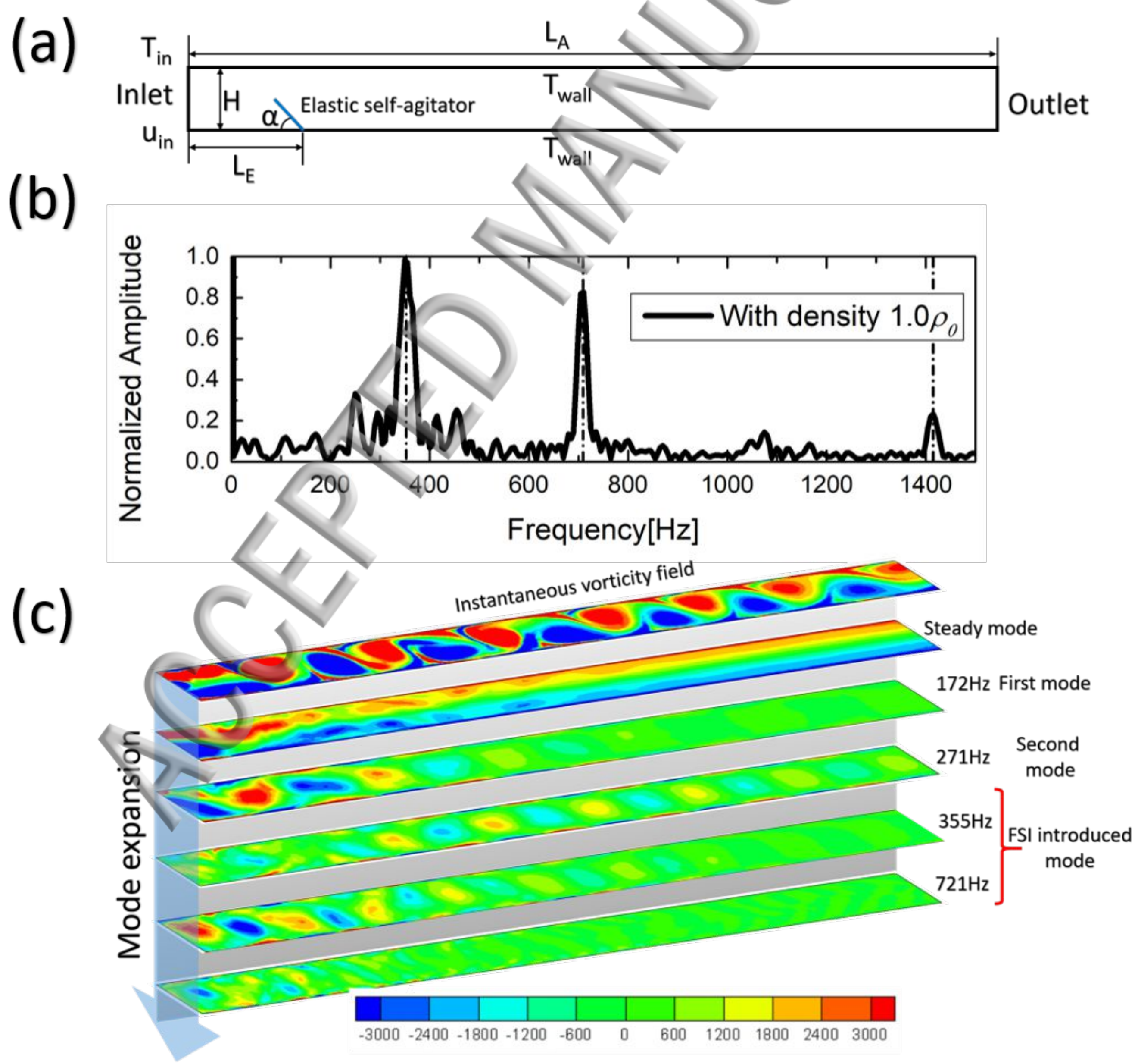
Figure 2. Numerical results and modal analysis: (a) 2-D assumption is applied to simplify the FSI process of the self-agitator; (b) To evaluate the structural oscillation frequency, Fourier analysis is performed on the maximum displacement of the self-agitator; (c) A series of snapshots of the transient vorticity fields are used for DMD analysis. Only the first few low-frequency modes are included here.

Figure 3. Results comparison for different densities. (a) Eigenfrequencies changing with density are performed for self-agitator with time averaged shape in FSI simulation; (b) Fourier analysis for different density self-agitators. The results show that with designed densities, the desired frequencies are achieved; (c) DMD results for $1.7\rho_0$ condition, the mode with 287Hz is enhanced; (d) DMD results for $4.0\rho_0$ condition, the mode with 186Hz is enhanced; (e) With the designed densities, the thermal performance can be improved comparing with the original one.

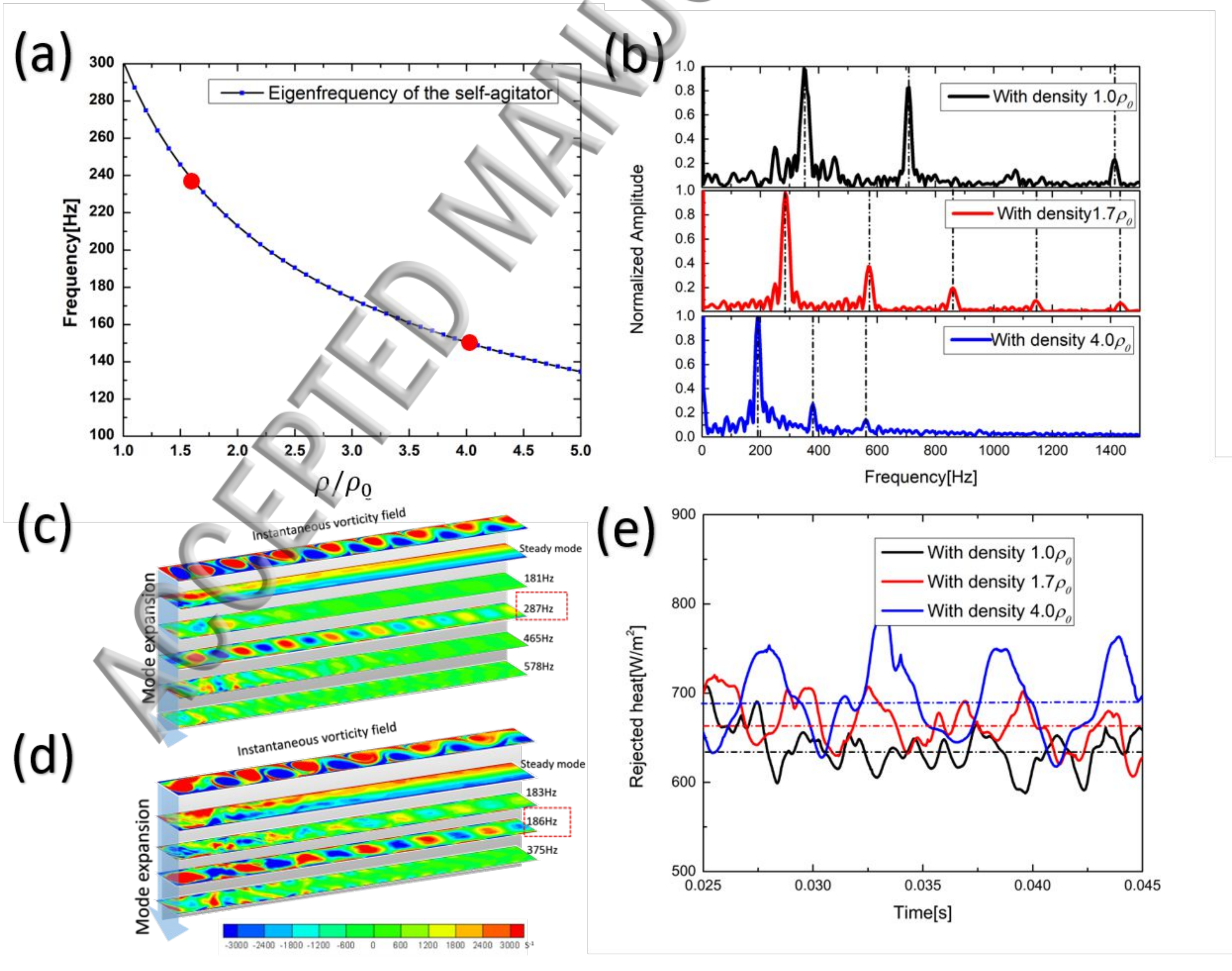
Figure 4. Self-agitator motions. (a) Two self-agitators are set in one row and they are moving out-of-phase. Fourier analysis is performed with vibration amplitude. (b) Out-of-phase motions of self-agitators in one period are presented.

Figure 5. Results comparison. (a) Nu-Re, Two row of self-agitator can achieve better performance of four rows of LVGs. (b) Pumping power is calculated with pressure loss multiply velocity.

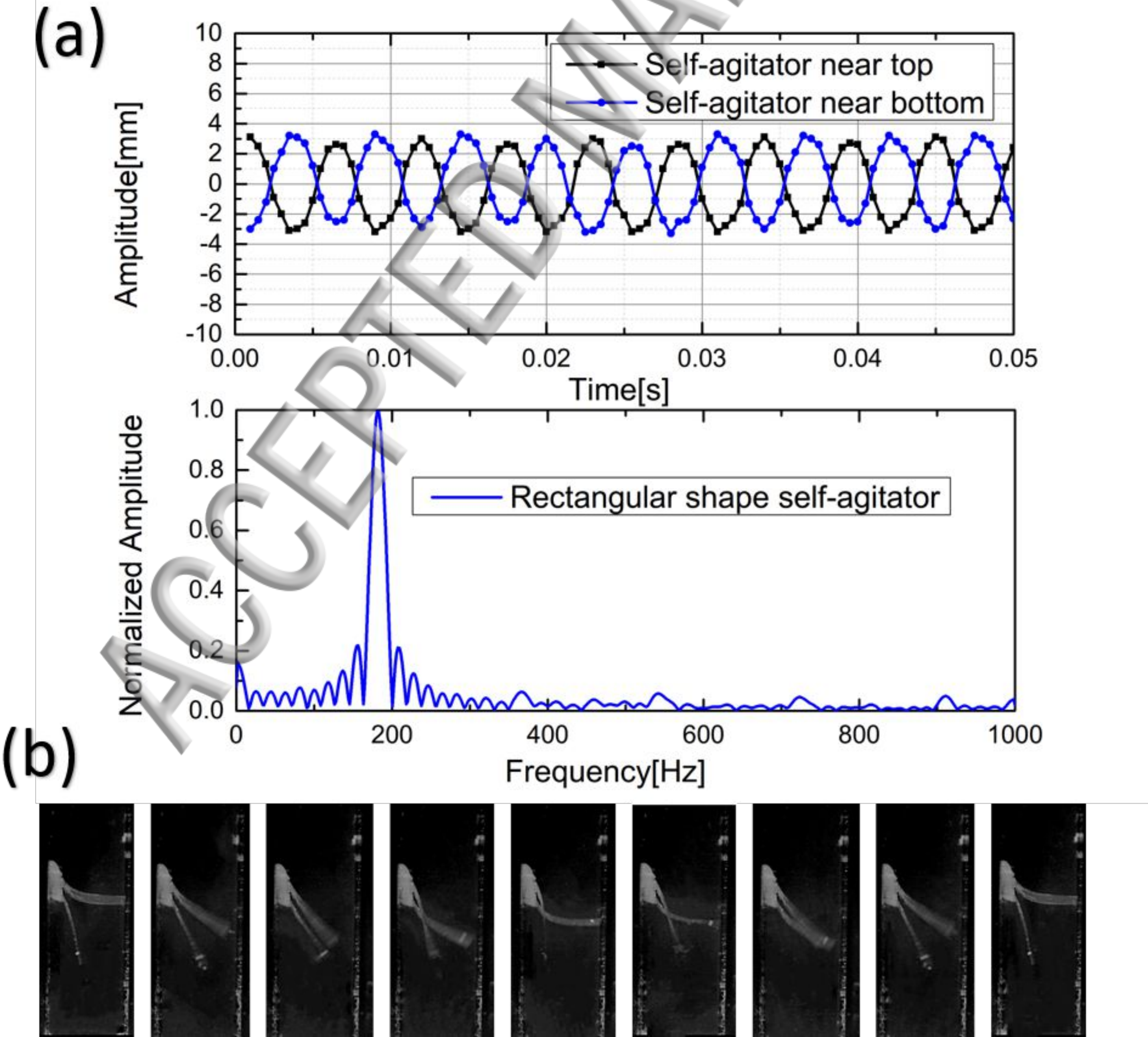

(a)
Inspired
Long time motion
Rectangular shape
Self-agitator
Blower
Flow bench
Wind tunnel
Sample
Heater
Flow direction
(b)
Pressure sensor
Pressure sensor
Fin
Hot air
Cold air
Heater

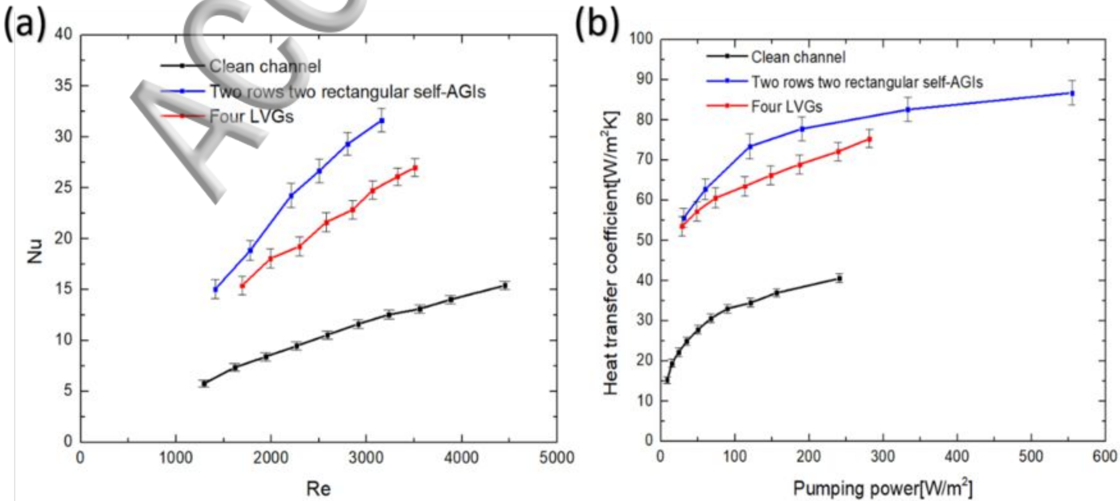


(a)
T_{in}
Inlet
u_{in}
L_A
H
α
Elastic self-agitator
T_{wall}
T_{wall}
L_E
Outlet
(b)
Normalized Amplitude
Frequency[Hz]
With density $1.0\rho_0$
(c)
Instantaneous vorticity field
Steady mode
172Hz First mode
271Hz Second mode
355Hz
721Hz
FSI introduced mode
Mode expansion
-3000 -2400 -1800 -1200 -600 0 600 1200 1800 2400 3000



(a)
Eigenfrequency of the self-agitator
Frequency[Hz]
ρ/ρ_0
(b)
With density $1.0\rho_0$
With density$1.7\rho_0$
With density $4.0\rho_0$
Normalized Amplitude
Frequency[Hz]
(c)
Instantaneous vorticity field
Steady mode
181Hz
287Hz
465Hz
578Hz
Mode expansion
(d)
Instantaneous vorticity field
Steady mode
183Hz
186Hz
375Hz
Mode expansion
-3000 -2400 -1800 -1200 -600 0 600 1200 1800 2400 3000 s^{-1}
(e)
With density $1.0\rho_0$
With density $1.7\rho_0$
With density $4.0\rho_0$
Rejected heat[W/m^2]
Time[s]


(a)
Self-agitator near top
Self-agitator near bottom
Amplitude[mm]
Time[s]
Normalized Amplitude
Rectangular shape self-agitator
Frequency[Hz]
(b)


(a)
Clean channel
Two rows two rectangular self-AGIs
Four LVGs
Nu
Re
0
5
10
15
20
25
30
35
40
0
1000
2000
3000
4000
5000
(b)
Clean channel
Two rows two rectangular self-AGIs
Four LVGs
Heat transfer coefficient[W/m²K]
Pumping power[W/m²]
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600