



THE IMPACT OF PIEZOELECTRIC STACK HEATING ON AIRCRAFT DEICING

Lang Yuan¹, Bo Miao¹, Kang Yan¹, Chunling Zhu^{1, *}

¹Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, People's Republic of China

Abstract

The phenomenon of aircraft icing poses a significant threat to flight safety. There is considerable potential for deicing techniques based on piezoelectric actuators. The focus of this paper is to examine the correlation between vibrational frequency / electric field intensity and heating properties of piezoelectric stack, as well as the effect of the piezoelectric stack heating on deicing. The findings indicate that the heating rate of the piezoelectric stack is significantly affected by its vibrational frequency and electric field intensity. Short-term and low frequency (below 1000 Hz) vibration of the piezoelectric stack at -16 °C of environment have slight impact on deicing.

Keywords: piezoelectric stack, vibration, heating properties, deicing, resonance.

1. Introduction

The accumulation of ice on the wings and other components not only increases the aircraft's flight weight, but also alters its aerodynamic profile, posing a serious threat to flight safety[1-3]. To address this issue, various anti/de-icing methods have been rapidly developed[4-7]. Among them, piezoelectric deicing technology based on mechanical vibration has gained increasing attention due to its advantages of low energy consumption, lightweight design and easy maintenance[8-11]. The fundamental principle of piezoelectric deicing technology lies in actuating piezoelectric actuators to induce structural resonance, thereby generating sufficient shear stress at the substrate/ice sheet interface to effectively achieve the objective of deicing[12-13]. Ramanathan et al. initially introduced the concept of piezoelectric deicing technology in 2000. They conducted a comparative analysis on the de-icing efficacy of PZT-5A and PZT-8 piezoelectric ceramics, revealing that at frequencies of 1.166 MHz and voltage levels of 75 V, PZT-8 demonstrated superior ice melting capabilities [14]. Palacios et al. mention the observation of ice cracking and melting when piezoelectric actuators are used at a frequency of 130 KHz [15]. Endres et al. compared the deicing effectiveness of low frequency de-icing (LFDI) and electric pulse de-icing (EIDI). The results indicate that ice melting is observed at 950 Hz and 1000 V for LFDI. However, no deicing was observed at -3 °C, perhaps due to the alteration in vibration characteristics caused by ice melting [16]. Palanque has carried out some research on the thermal effects of actuators, and it was found that at the resonance frequency the structure and actuator heat more markedly at the resonance frequency [17]. Several scholars have studied the coupling characteristics of wave vibration and heating in order to achieve the purpose of deicing [18-21]. Heating of the piezoelectric actuator not only impacts the device's performance, but also influences its deicing effectiveness. This study examines the relationship between heating characteristics of the piezoelectric stack and both vibration frequency as well as electric field intensity, while observing the influence of piezoelectric stack heating on deicing.

2. Experiment Setups

In order to establish the correlation between vibration and heating characteristics of a piezoelectric

stack, this paper employs experiment setups as depicted in Figure 1. The experiment setups are divided into two parts: 1) the piezoelectric controller serves as the core device for exciting the piezoelectric stack. 2) Monitor and record the temperature of both the piezoelectric stack and aluminum plate using thermocouples, paperless recorders, and infrared cameras. The paperless recorder captures temperature data at one-second intervals. Figure 2 illustrates the distribution of thermocouples, which measure the temperatures of the piezoelectric stack as well as the upper and lower surfaces in the middle of the aluminum plate. The experiment was initially conducted at ambient temperature and subsequently in a low-temperature environment with the recorded experimental temperature being -16°C .

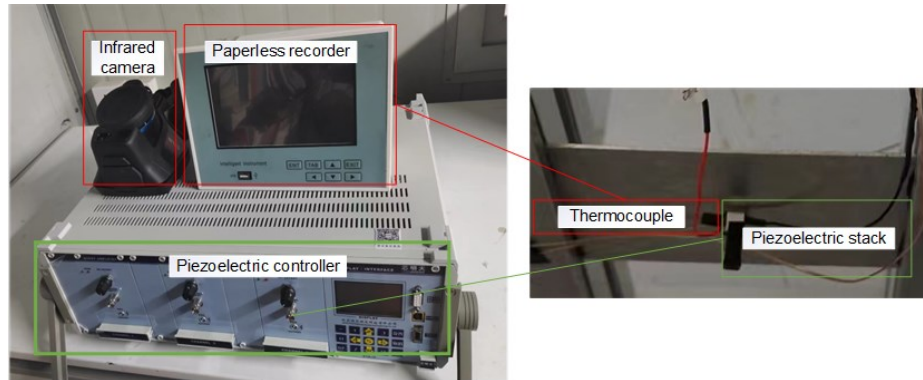


Figure 1 – Diagram of experiment setups.

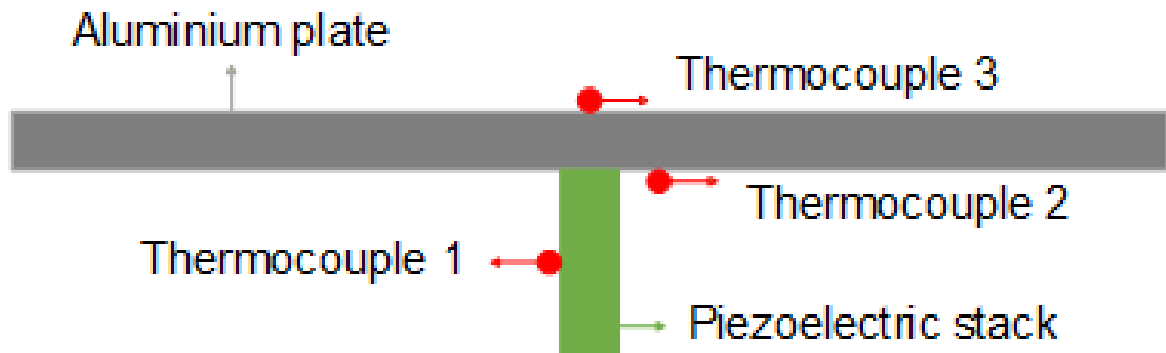


Figure 2 – Diagram of thermocouples distribution.

3. The effect of vibration frequency and electric field intensity

Extensive research has been conducted both domestically and internationally on the heating characteristics and underlying causes of piezoelectric piles. Zheng has conducted a comprehensive study on the thermal behavior of various piezoelectric stacks, and the experimental findings indicate that surface heat generation is primarily attributed to ferroelectric hysteresis in the absence of mechanical stress[22]. Härdtl explained that ferroelectric losses come from four primary mechanisms: movement of domain walls, a basic lattice loss, a loss related to microstructure, and conductivity loss[23]. The primary cause of heating in the piezoelectric stack is a result of dielectric and mechanical losses. Dielectric losses occur when energy dissipates within the material under an applied electric field, while mechanical losses are due to internal friction and hysteresis as the material undergoes deformation. These combined losses lead to an increase in temperature within the piezoelectric stack, which can impact its performance and longevity. Prichard calculated the heat transfer coefficient of the piezoelectric stack and the hysteresis loss per cycle[24]. Ronkanen proposed a revised model to mitigate the displacement loss resulting from the heating of piezoelectric

piles, aiming to minimize error in measurements[25]. Senousy conducted a scholarly investigation into the thermal properties of piezoelectric stack utilized as fuel injection ports, and further refined the displacement hysteresis model in a rigorous manner[26]. Wu investigated the impact of various bonding methods on the thermal performance of a dual-layer piezoelectric ceramic transducer[27]. Vasiljev conducted an analysis on the minimization of heat and maximization of heat dissipation in high-power Langevin piezoelectric transducers[28]. Ramesh conducted an investigation into the thermal characteristics of ultrasonic transducers operating under resonant and non-resonant conditions, revealing that surface resonance led to a more pronounced heating effect[29]. The temperature rise expression of a stress-free piezoelectric stack is given by the following equation[22]:

$$q_G = u f v_e \quad (1)$$

$$\Delta T = q_G / k(T) A \quad (2)$$

q_G represents the heat production of the actuator, u denotes the dielectric loss generated per unit volume per vibration cycle and is directly correlated to the electric field strength, f stands for the vibration frequency, v_e indicates the effective volume causing heat, ΔT represents the temperature rise, $k(T)$ is the total heat transfer coefficient, and A signifies the total surface area of the actuator. The heating of a piezoelectric stack is closely correlated with the intensity of the electric field (E) and the frequency of vibration (f). This section examines the relationship between q_G and E/f of a piezoelectric stack at room temperature, followed by an investigation into the impact of cold environments on the heating characteristics of a piezoelectric stack.

3.1 Vibration frequency

Firstly, the impact of vibration frequency on the thermal behavior of piezoelectric stack is examined. Due to the power restriction of the piezoelectric controller, the vibration frequency is set to 100 Hz-1000 Hz and the voltage is set to 80 V. Simultaneously, the duration of vibration is set at 5 minutes. However, if the temperature of the piezoelectric stack reaches a set upper limit (85 °C), excitation will be halted. Experiments were conducted in both cold and conventional environments to more accurately simulate real aircraft icing conditions. Temperature data is recorded at one-second intervals, and to mitigate the impact of varying initial temperatures, the starting temperature is utilized as the baseline for data analysis.

Figure 3 illustrates the temperature rise characteristics exhibited by the piezoelectric stack. The graph a) illustrates the heating properties of the piezoelectric stack at ambient temperature. It is evident from the graph that as the frequency increases, the temperature of the piezoelectric stack rises progressively, and the time required to reach the limit temperature (85 °C) decreases accordingly. Initially, during vibration, there is a linear increase in the temperature rise of the piezoelectric stack. As vibration duration extends, the piezoelectric stack gradually attains a thermally stable state. The temperature rise characteristics of piezoelectric piles in a cold environment (-17 °C) are depicted in the b) figure. It is evident from the graph that the heating behavior of piezoelectric piles in a cold environment aligns closely with those in conventional conditions. However, the cold environment does result in a deceleration of the heating rate of the piezoelectric stack, leading to an increase in the time required for reaching the limit temperature. Additionally, the cold environment amplifies the maximum temperature differential of the piezoelectric stack. This surface cold environment is advantageous for mitigating the heating issue of the piezoelectric reactor. The figure c) shows the heating rate of piezoelectric piles under two conditions. Under conventional temperature conditions, the heating rate of piezoelectric pile increases linearly with the increase of frequency. But there was an inflection point at 500 Hz, and the cold environment delayed the inflection point to 800 Hz. The heating rate of the piezoelectric stack is notably diminished in low temperature environments, especially above 500 Hz. For a given vibration duration, the temperature difference of the piezoelectric stack increases with an increase in frequency. In other words, the heating rate of the piezoelectric stack also increases with higher frequencies. Additionally, there is a significant reduction in the time required for the piezoelectric stack to reach the same temperature. It is crucial to remain

vigilant about potential damage caused by high temperatures as they can adversely affect both performance and service life of piezoelectric stack. Fortunately, the cold environment can mitigate the adverse effects of piezoelectric pile heating on the device itself.

The heating rate of the plate under various vibration frequencies is illustrated in Figure 4. In addition to a frequency of 300 Hz, the heating rate on both sides of the aluminum plate increases proportionally with the piezoelectric stack vibration frequency. Simultaneously, thermocouple 2 exhibits a higher heating rate compared to thermocouple 3, aligning with fundamental principles of thermal dynamics. The discrepancy arises from the fact that in low-temperature environments and under low-frequency vibrations, the temperature rise of the aluminum plate is not readily discernible. A piezoelectric stack undergoes vibrations at a frequency of 1000 Hz for a duration of 127 seconds in an environment with a low temperature of -16 °C, resulting in the aluminum plate experiencing a temperature rise of 2 °C. Distinctly, higher external temperatures, vibration frequencies, and durations can lead to ice melting and alter the mechanical vibration characteristics of the system, thereby impacting the deicing effectiveness, this is the same as Endres et al[16].

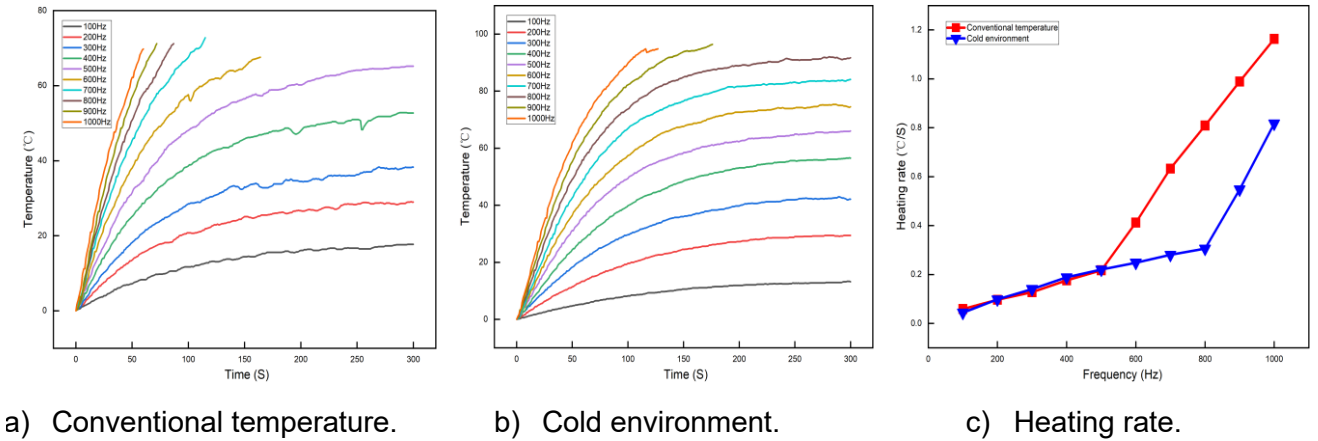


Figure 3 – Effect of frequency on heating characteristics of piezoelectric stack.

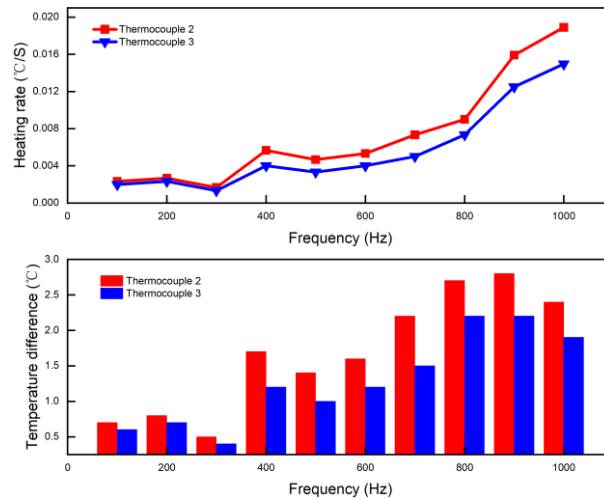


Figure 4 – Effect of frequency on heating characteristics of both sides of a plate.

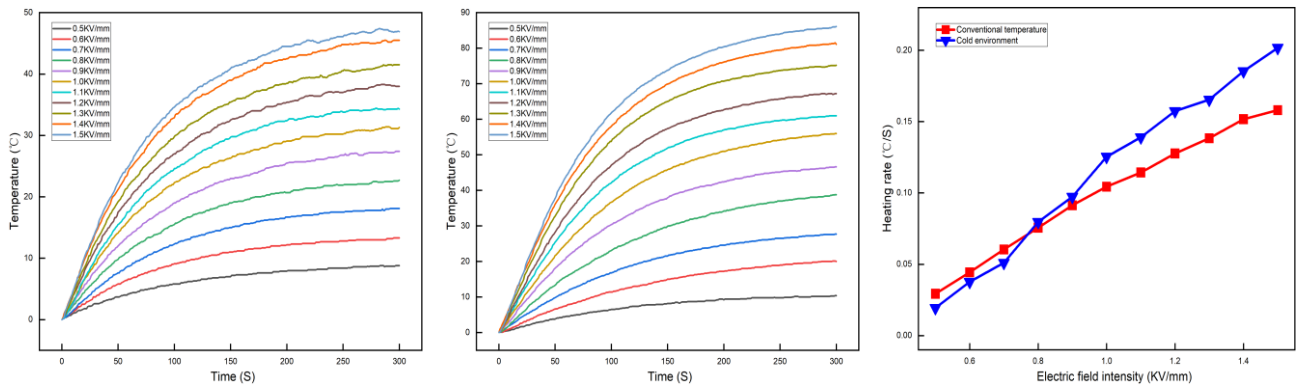
3.2 Electric field intensity

The frequency is set at 200 Hz, with the voltage ranging from 50 V to 150 V, in order to investigate the impact of electric field intensity. Furthermore, the piezoelectric stack has a single layer thickness of 100 μm .

Figure 5 illustrates the impact of electric field strength on the heating of a piezoelectric stack. As the

electric field intensity increases, the heating of the piezoelectric stack becomes more pronounced, resulting in a higher heating rate. However, unlike the effect of frequency, vibrating at 150 V for 5 minutes did not cause the piezoelectric stack to reach its upper limit temperature (85 °C). The graph c) depicts the variation in heating rate of a piezoelectric stack with changes in electric field under two different environments. As the electric field increases, the heating rate of the piezoelectric stack shows predominantly linear growth, particularly at room temperature. However, in a cold environment and especially at higher voltages, the heat loss of one cycle vibration of the device increases due to the adverse impact of low temperatures on the performance of the piezoelectric stack, leading to an elevation in the heating rate, unlike the frequency effect.

Figure 6 shows the variation of the temperature on both sides of the plate with the electric field temperature in a cold environment. The heating rate of the plate is directly proportional to the electric field intensity, while the influence of the electric field intensity on the temperature rise of the plate is relatively less significant compared to that of vibration frequency. When the piezoelectric stack vibrates at 50 V, a negative thermal equilibrium of the plate is observed, resulting in a decrease in plate temperature. As the voltage applied to the piezoelectric stack increases to 150 V, the plate experiences a maximum temperature increase of 2.4 °C. With further increments in voltage, the temperature rise of the plate becomes more pronounced and may potentially lead to ice melting.



a) Conventional temperature.

b) Cold environment.

c) Heating rate.

Figure 5 – Effect of electric field intensity on heating characteristics of piezoelectric stack.

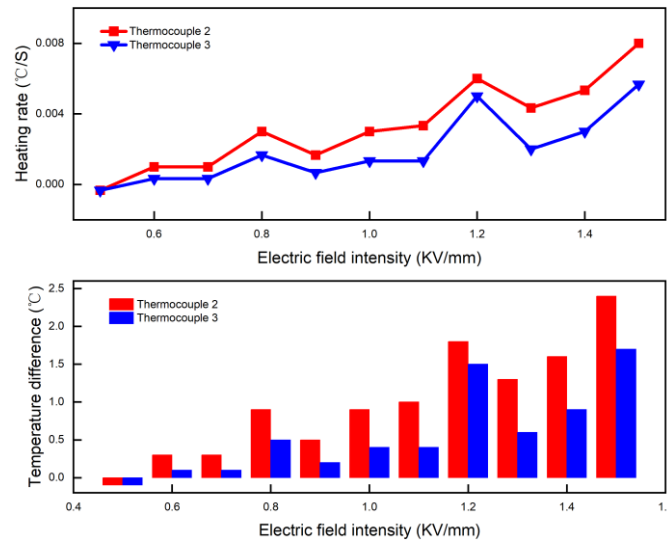


Figure 6 – Effect of electric field intensity on heating characteristics of both sides of a plate.

4. Resonance effect

Piezoelectric deicing technology utilizing low frequency vibration can effectively achieve deicing through the induction of system resonance. The entire investigation can be segmented into the subsequent stages:

- By utilizing finite element simulation software, the primary resonance frequency for deicing is determined to be 464 Hz.
- Sweep the deicing system using a laser vibrometer at intervals of 20 Hz within the frequency range of 200 to 600 Hz. The resulting resonance frequency is 360 Hz.
- Sweep the deicing system using a laser vibrometer at intervals of 1 Hz within the frequency range of 340 Hz to 380 Hz. The exact resonance frequency is 363 Hz.
- The deicing system was operated at 50 V voltage and 363 Hz frequency in both normal temperature and cold environments to investigate the impact of resonance on the heating characteristics of the piezoelectric stack and system.

Due to the first-order resonance frequency being 363 Hz, comparative analysis was conducted using 300 Hz and 400 Hz. Figure 7 illustrates the heating characteristics of piezoelectric stack under two different conditions. Under normal temperature conditions, the temperature difference and heating rate of 300 Hz and 363 Hz are equivalent. However, in a cold environment, the temperature difference and heating rate of 363 Hz are relatively lower compared to those of 300 Hz. This is contrary to the law that the heating of piezoelectric stack is proportional to the frequency. Resonance has been shown to effectively mitigate the thermal effects observed in piezoelectric stack. Figure 8 illustrates the heating characteristics of the plate at its resonance frequency. In a conventional environment, the temperature difference and heating rate of thermocouple 2 are observed to be the highest among the three frequencies. When the system exhibits resonance in a cold environment, the temperature difference and heating rate at 363 Hz closely approximate those at 400 Hz, with particular emphasis on the identical temperature difference observed at thermocouple 3. The findings demonstrate that the resonant system effectively mitigates the heating of the piezoelectric pile and enhances the heating of the plate during resonance. This phenomenon can be attributed to the resonance-induced enhancement in both the conversion efficiency of the piezoelectric stack and mechanical vibration within the system. The thermal shock experienced by the amplifying resonant system provides additional evidence for the potential of ice melting through piezoelectric deicing methods.

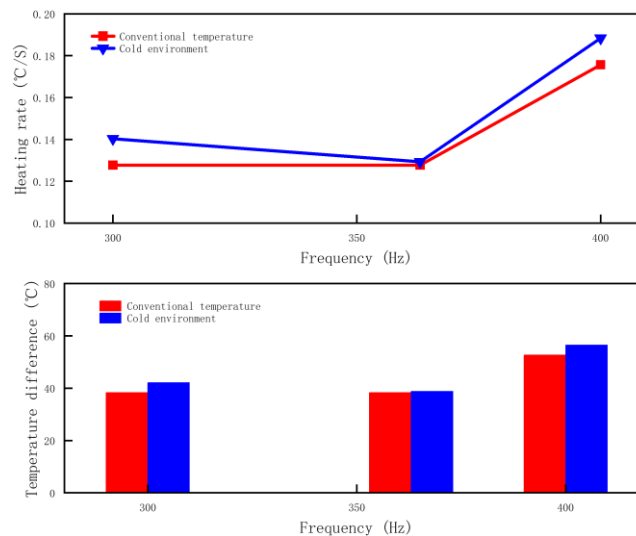


Figure 7 – Effect of resonance on heating characteristics of piezoelectric stack.

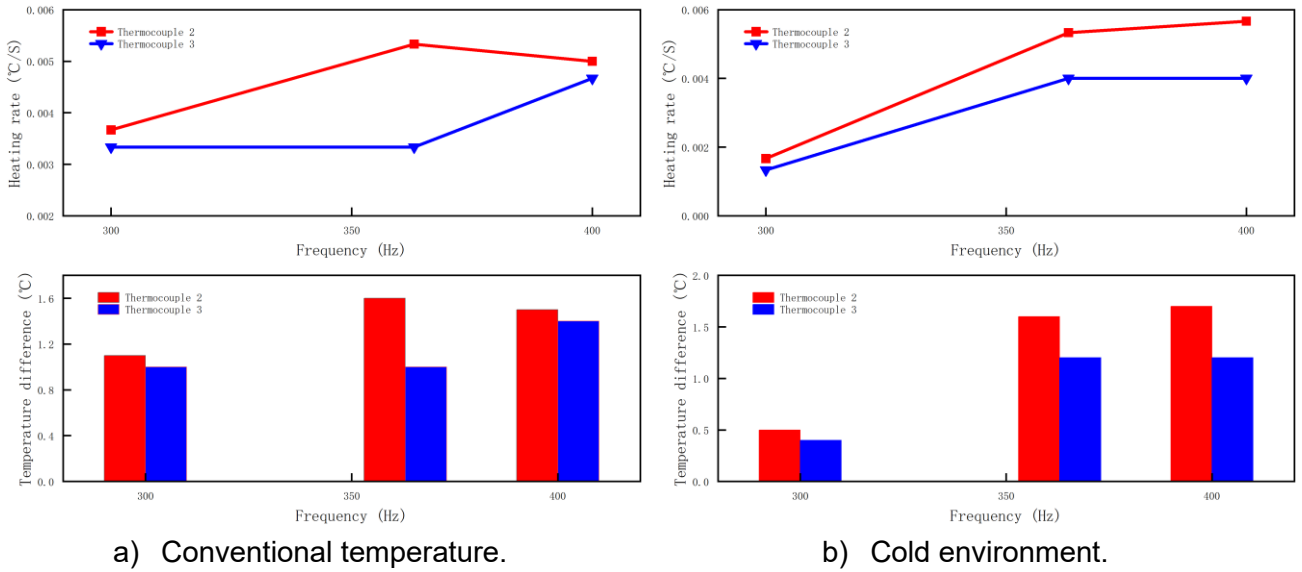


Figure 8 – Effect of electric field intensity on heating characteristics of both sides of a plate.

5. Conclusion

The heating characteristics of the piezoelectric stack exhibit a direct proportionality to both the frequency and intensity of the electric field. The resonance phenomenon within the deicing system effectively mitigates heat generation in the piezoelectric stack while simultaneously enhancing heat transfer to the plate. In an environment with temperatures as low as -16°C , it is highly unlikely for ice to thaw in the piezoelectric stack when subjected to 150 V and 1000 Hz excitation. However, with increasing ambient temperature, voltage, and frequency, particularly when the deicing system is in a resonance state, there exists potential for effective ice melting through piezoelectric deicing technology. It is imperative to monitor interface temperature during investigations into piezoelectric deicing technology in order to prevent unintended ice melting, which could lead to alterations in the mechanical properties of the system.

6. Contact Author Email Address

Email: yl1998@nuaa.edu.cn

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References

- [1] Yamazaki M, Jemcov A, Sakaue H. *A review on the current status of icing physics and mitigation in aviation*[J]. *Aerospace*, 2021, 8(7): 188.
- [2] Tetteh E, Loth E, Neuteboom M O, et al. *In-flight gas turbine engine icing*[J]. *AIAA Journal*, 2022, 60(10): 5610-5632.
- [3] Bromfield M A, Horri N, Halvorsen K, et al. *Loss of control in flight accident case study: icing-related tailplane stall*[J]. *The Aeronautical Journal*, 2023: 1-20.
- [4] Khalil E E, Said E, AlSaheh A, et al. *Effect of hot air jet arrangement from a piccolo tube in aircraft wing anti-icing system*[C]//*AIAA Propulsion and Energy 2020 Forum*. 2020: 3952.
- [5] Zhou W, Liu Y, Hu H, et al. *Utilization of thermal effect induced by plasma generation for aircraft icing mitigation*[J]. *AIAA Journal*, 2018, 56(3): 1097-1104.
- [6] Sommerwerk H, Luplow T, Horst P. *Numerical simulation and validation of electro-impulse de-icing on a leading edge structure*[J]. *Theoretical and Applied Fracture Mechanics*, 2020, 105: 102392.
- [7] Zhang H, Zhao G, Wu S, et al. *Solar anti-icing surface with enhanced condensate self-removing at extreme environmental conditions*[J]. *Proceedings of the National Academy of Sciences*, 2021, 118(18): e2100978118.
- [8] Villeneuve E, Volat C, Ghinet S. *Numerical and experimental investigation of the design of a piezoelectric de-icing system for small rotorcraft part 3/3: Numerical model and experimental validation of vibration-based de-icing of a flat plate structure*[J]. *Aerospace*, 2020, 7(5): 54.
- [9] Awada A, Younes R, Ilinca A. *Optimization of wind turbine performance by vibration control and deicing*[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2022, 229: 105143.
- [10] Miao B, Li W, Yuan L, et al. *Determining region of installation of flat-ended piezoelectric de-icing actuators on curved surfaces*[J]. *Journal of Aircraft*, 2023, 60(1): 232-244.
- [11] Miao B, Yuan L, Zhu C L. *Distribution characteristics of de-icing shear stress on thin Plate with out-of-Plane flexural vibration mode*[J]. *Transactions of Nanjing University of Aeronautics & Astronautics*, 2023, 40.
- [12] Adachi K, Saiki K, Sato H. *Suppression of frosting on a metal surface using ultrasonic vibrations*[C]//*1998 IEEE Ultrasonics Symposium*. Proceedings (Cat. No. 98CH36102). IEEE, 1998, 1: 759-762.
- [13] Adachi K, Saiki K, Sato H, et al. *Ultrasonic frost suppression*[J]. *Japanese journal of applied physics*, 2003, 42(2R): 682.
- [14] Ramanathan S, Varadan V V, Varadan V K. *Deicing of helicopter blades using piezoelectric actuators*[C]//*Smart Structures and Materials 2000: Smart Electronics and MEMS*. SPIE, 2000, 3990: 281-292.
- [15] Palacios J, Zhu Y, Smith E, et al. *Ultrasonic shear and lamb wave interface stress for helicopter rotor de-icing purposes*[C]//*47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 14th AIAA/ASME/AHS Adaptive Structures Conference 7th*. 2006: 2282.
- [16] Endres M, Sommerwerk H, Mendig C, et al. *Experimental study of two electro-mechanical de-icing systems applied on a wing section tested in an icing wind tunnel*[J]. *CEAS Aeronautical Journal*, 2017, 8: 429-439.
- [17] Palanque V. *Design of low consumption electro-mechanical de-icing systems*[D]. Université de Toulouse; ISAE-Supaero, 2022.
- [18] Zeng X C, Yan Z X, Lu Y C, et al. *Reduction of ice adhesion using surface acoustic waves: nanoscale vibration and interface heating effects*[J]. *Langmuir*, 2021, 37(40): 11851-11858.
- [19] Jacob S, Pandey S, Moral J D, et al. *Surface acoustic waves equip materials with active de-icing functionality: unraveled glaze ice de-icing mechanisms and application to centimeter-scale transparent surfaces*[J]. *Advanced Materials Technologies*, 2023: 2300263.
- [20] Nampoothiri K N, Nath A, Satpathi N S, et al. *Deicing of sessile droplets using surface acoustic waves*[J]. *Langmuir*, 2023, 39(11): 3934-3941.
- [21] Del Moral J, Montes L, Rico-Gavira V J, et al. *A holistic solution to icing by acoustic waves: de-icing, active anti-icing, sensing with piezoelectric crystals, and synergy with thin film passive anti-icing solutions*[J]. *Advanced Functional Materials*, 2023, 33(15): 2209421.
- [22] Zheng J, Takahashi S, Yoshikawa S, et al. *Heat generation in multilayer piezoelectric actuators*[J]. *Journal of the American Ceramic Society*, 1996, 79(12): 3193-3198.
- [23] Härdtl H H. *Electrical and mechanical losses in ferroelectric ceramics*[J]. *Ceramics International*, 1985, 11(4): 150.
- [24] Pritchard J, Ramesh R, Bowen C R. *Time-temperature profiles of multi-layer actuators*[J]. *Sensors and Actuators A: Physical*, 2004, 115(1): 140-145.
- [25] Ronkanen P, Kallio P, Vilkkio M, et al. *Self heating of piezoelectric actuators: Measurement and compensation*[C]//*Micro-Nanomechatronics and Human Science, 2004 and The Fourth Symposium Micro-Nanomechatronics for Information-Based Society*, 2004. IEEE, 2004: 313-318.
- [26] Senousy M S, Rajapakse R, Mumford D, et al. *Self-heat generation in piezoelectric stack actuators used in fuel*

- injectors*[J]. *Smart Materials and Structures*, 2009, 18(4): 045008.
- [27]Wu Z, Cochran S. *Loss effects on adhesively-bonded multilayer ultrasonic transducers by self-heating*[J]. *Ultrasonics*, 2010, 50(4-5): 508-511.
- [28]Vasiljev P, Mazeika D, Borodinas S. *Minimizing heat generation in a piezoelectric Langevin transducer*[C]//2012 *IEEE International Ultrasonics Symposium*. IEEE, 2012: 2714-2717.
- [29]Ramesh R, Kumar R K, Kumar T K V. *Heat generation in 1–3 piezoceramic—polymer composites*[J]. *Journal of Electroceramics*, 2013, 30(4): 251-257.