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Frost Defrosting Control System for Air-Source Heat Pump Based on Nighttime Adaptive Image Gray-Scale Recognition

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Abstract: ***This paper introduces an intelligent defrosting control system for air-source heat pumps based on nighttime adaptive image grayscale recognition. The system aims to address the frequent false actions and low energy efficiency of traditional defrosting technologies (such as the temperature-time method) in low-temperature and high-humidity environments. Its core innovation lies in directly capturing images of the heat exchanger fin surface via a low-illumination camera equipped with infrared fill light and identifying the frost layer using image grayscale processing technology.***

Keywords: Air-source heat pumps, Defrosting, Gray-Scale, Image recognition**.**

1. Overview

1.1 Background

As a clean, low-carbon, and high-efficiency energy equipment, air-source heat pumps have been deployed on a large scale across various sectors. They serve as a crucial pillar for advancing the “Dual Carbon” goals, offering significant carbon reduction and energy savings compared to traditional heating methods. However, in low-temperature and high-humidity environments, the outdoor heat exchanger is prone to frost formation, which has become a core bottleneck limiting operational performance. The frost layer substantially increases thermal and air flow resistance, leading to a sharp decline in heat transfer efficiency and a surge in compressor power consumption. Not only does defrosting interrupt heating and cause indoor temperature fluctuations, but it also accelerates component wear, shortens equipment lifespan, and severely impacts energy efficiency and economy. Therefore, precise defrosting is a prerequisite for ensuring stable winter operation.

China’s national “Dual Carbon” strategy explicitly promotes the intelligent upgrading of heat pump equipment, and industry standards also impose rigid requirements for frost control performance, providing direction for defrosting technology innovation. However, existing technologies have notable shortcomings: traditional methods like temperature-time control are prone to false or missed defrosting; image recognition is limited by nighttime lighting conditions; and direct frost measurement faces challenges in large-scale application due to point monitoring and cost constraints. These defects create a significant gap with policy requirements and practical needs. Based on this, this study integrates area-source compensated lighting, multi-parameter models, and image processing technology to break through traditional bottlenecks and provide a solution for defrosting technology upgrades.

Existing defrosting technologies domestically and internationally are mainly divided into three categories: First, the widely used Temperature-Time (TT) control method, which is simple and inexpensive but has a high rate of false defrosting and does not consider regional meteorological differences. Second, the TEPS photoelectric frost sensing method, which can directly detect frost presence but relies on preset thresholds and cannot accurately reflect the physical state of frost accumulation. Third, the THT zonal frost mapping control method, which evaluates defrost timing through multi-parameter accumulation but suffers from insufficient sensor accuracy and dynamic adaptability, still carrying misjudgment risks. Image recognition-based frost measurement technology has become a research hotspot, but issues like nighttime lighting adaptation and engineering promotion costs have not been fully resolved.

1.2 Introduction

This project develops a frost defrosting control system for air-source heat pumps based on nighttime adaptive image gray-scale recognition. It aims to break through the lighting limitations and accuracy bottlenecks of traditional defrosting technologies, achieve all-weather precise monitoring and intelligent defrosting of frost layers, reduce the rate of false defrosting and energy consumption, improve the operational stability and energy efficiency of air-source heat pumps, and provide technical support for carbon emission reduction in the building sector.

Optimize nighttime frost layer image acquisition and processing technology, combining infrared fill-light devices and low-light enhancement algorithms to achieve clear acquisition and feature extraction of frost layer images under different lighting conditions.

Construct a multi-parameter fusion model integrating “image gray scale - ambient temperature - operating duration,” establish quantitative calculation methods for frost area ratio (S), frost density (ρ), and relative frost amount (F), and dynamically correct defrosting thresholds.

Develop an integrated defrosting controller comprising hardware (CMOS camera, temperature controller, industrial computer) and software (Python programming + image recognition algorithm), supporting real-time data transmission and intelligent control.

Verify the controller's adaptability in different climate zones (low-temperature high-humidity, cold and dry). Compared to traditional methods, it aims to achieve a false defrosting rate of ≤3% and a significant improvement in the energy efficiency ratio (COPm).

2. Theoretical Research on Image Recognition for Frost Measurement

2.1 Principles of the Image Recognition Frost Measurement Method

As an important branch of artificial intelligence research, image recognition technology relies on images. It involves computer processing, analyzing, and understanding the content of images, ultimately completing the recognition of different pattern targets and objects. Currently, this technology has permeated various fields: in security, applications like facial recognition and fingerprint recognition depend on it; in the military, tasks such as terrain surveying and aircraft identification require it; in transportation, scenarios like traffic sign recognition and license plate number identification also rely on it. Meanwhile, research achievements in image recognition technology have laid an important foundation for the development of higher-level fields like image understanding, robotics, and autonomous driving.

2.1.1 Image Acquisition and Processing

Image acquisition technology enables the conversion from continuous optical images to single-frame digital images. Its core process includes three steps: sampling, quantization, and encoding. If the acquired images contain noise, corresponding measures need to be taken to eliminate it. Main methods include median filtering, arithmetic mean filtering, smoothing linear filtering, and Gaussian filtering. Furthermore, for images with blurred edges, sharpening can be performed using differentiation methods or high-pass filtering to make the image clearer.

When dealing with the frosted surface of an air-source heat pump heat exchanger, the camera position can be fixed for shooting, and photos can be captured and saved at the same time interval.

To highlight key features and optimize storage and transmission, images are converted to grayscale by removing color interference. During image processing, true color is typically described by three components: Red (R), Green (G), and Blue (B), which are the primary colors. The value of each component ranges from 0 to 255. A grayscale image is obtained when the R, G, and B values for each pixel in the image are equal.

For a standard grayscale image, the grayscale value of any pixel is an integer between 0 and 255. Pixels with lower grayscale values appear darker, while those with higher values appear whiter.

2.1.2 Image Feature Information Recognition

After grayscale processing, the image contains only brightness information, no longer color information. The brightness of a single pixel point in the image can be reflected by its grayscale value. Therefore, the threshold segmentation method is used to determine whether frost is present on the heat exchanger fin surface. A specific grayscale value is selected as the threshold for frost pixel points. All pixel points are divided into frost pixels and non-frost pixels based on this threshold, thereby achieving effective recognition of the frost area. The threshold is generally taken as the average grayscale value of the frost-free fin surface.

Assume f (x, y) is the grayscale value of the pixel at spatial coordinates (x, y) in the acquired image, and fi is the grayscale threshold for frost pixel points. The judgment logic is as follows: if the grayscale value f (x, y) at coordinates (x, y) is ≥ fi, it is judged as a frost point; if f (x, y) < fi, it is judged as a non-frost point.

Furthermore, the "Frost Layer Area Ratio Coefficient (S)" is introduced. This coefficient reflects the size of the frost area on the fin surface, obtained by dividing the number of frost pixel points by the total number of pixel points on the heat exchanger fin surface, as expressed in Equation (1):

$$S=n/N \tag{1}$$

Where:

n - number of frost pixel points;
N - total number of pixel points on the heat exchanger fin surface;
S - frost layer area ratio coefficient.

During the actual frosting process of the unit, the frost layer expands "laterally" across the fin surface and accumulates "longitudinally" into the fin interior, causing the frost density per pixel point to continuously increase. Therefore, the "Frost Layer Density Identification Coefficient (ρ)" is introduced, reflecting the longitudinal growth degree of the frost layer on the unit's heat exchanger fins. Its value is the ratio of the average grayscale value of frost pixel points to the theoretical maximum grayscale value of the image, as expressed in Equations (2) and (3):

$$\bar{f}' = \sum f/n \tag{2}$$

$$\rho = \frac{\bar{f}'}{255} \tag{3}$$

Where:

f - total grayscale value of frost pixel points;
$\bar{f}'$ - average grayscale value of frost pixel points;
ρ - frost layer density identification coefficient.

In the final stage, by multiplying the frost layer area ratio coefficient (S) and the frost layer density identification coefficient (ρ), the key image feature information—"Frost Quantity Identification Characteristic Parameter (Q)"—is obtained. This parameter comprehensively reflects the unit's frosting degree from both "lateral" (frost coverage) and "longitudinal" (frost density) dimensions. Theoretically, it can accurately characterize the actual frost accumulation of the unit and serves as a reliable basis for defrost judgment. Its expression is shown in Equation (4):

$$Q=S\cdot\rho \tag{4}$$

Where:

Q - frost quantity identification characteristic parameter.

2.2 Traditional Image Recognition Frost Measurement Theory

Academia has proposed various image recognition schemes to cope with variable lighting conditions:

1) Extracting illumination-invariant features method: Attempts to extract features unaffected by lighting by performing illumination normalization or embossing on images. This method is effective when lighting changes are gradual but performs poorly under drastic changes like day-night alternation. Furthermore, all-day high-intensity fill lighting leads to increased energy consumption.

2) Appearance-Based method: This method relies on a large database containing samples under various lighting conditions for recognition through comparison. It involves significant workload and requires the lighting conditions of the image to be recognized to highly match those in the sample library, resulting in poor applicability in practical engineering.

3) Class-Based method: This method requires precise prior knowledge of the target's shape and reflective properties to build a model. However, modeling is extremely difficult for frost layers with variable morphology and uneven distribution, making it significantly limited.

2.3 Nighttime Adaptive Image Recognition Frost Measurement Theory

Although traditional image recognition frost measurement methods have advantages in principle, their accuracy faces severe challenges in practical applications, especially in outdoor environments with day-night alternation and lighting changes. While stable fill lighting can be used at night, if there is external light interference or fluctuation in fill light intensity, recognition methods with fixed thresholds can still produce significant errors. Therefore, developing a frost measurement theory capable of adapting to lighting changes, especially nighttime adaptation, is crucial.

To this end, this project innovatively introduces the concept of a "Reference Illumination Area Source" and proposes a lighting-adaptive scheme specifically for image-based frost measurement.

The core idea of this theory is to use a reference area unaffected by frost but varying with lighting (i.e., the "Reference Illumination Area Source") to calibrate the current lighting intensity in real-time and dynamically correct the key parameters of the recognition algorithm accordingly.

1) Adaptive Correction of Frost Grayscale Threshold

Let the initial reference grayscale value be f_0, and the initial frost grayscale threshold be f_i. When environmental lighting changes cause the grayscale value of the reference area source to become f_a, the new frost grayscale threshold f_i' is corrected according to Equation (2-5):

$$f_i' = f_i + \delta_1(f_0 - f_a) \tag{5}$$

Where δ_1 is the threshold correction compensation coefficient, related to the material of the reference area source and the fins, with a value range of 0.6 to 0.9, recommended as 0.8. This correction ensures accurate segmentation between frosted and non-frosted regions under different lighting conditions.

2) Adaptive Correction of Frost Layer Density Identification

Lighting changes also affect the absolute grayscale value of the frost area. To eliminate this effect, the average grayscale value of frost pixel points is corrected, as shown in Equation (6):

$$\bar{f}' = \bar{f} - \delta_2(f_0 - f_a) \tag{6}$$

Where $\bar{f}'$ is the corrected average grayscale value, and δ_2 is the frost quantity correction compensation coefficient, with a value range of 0.1 to 0.3, recommended as 0.2.

The corrected frost layer density identification coefficient ρ is calculated according to Equation (7):

$$\rho = \frac{\bar{f}'}{255} \tag{7}$$

Finally, the frost quantity identification characteristic parameter Q is calculated via $Q = S \times \rho$. Through this series of real-time corrections, the algorithm can effectively resist interference caused by nighttime fill light fluctuations or day-night lighting transitions, ensuring the accuracy and reliability of frost quantity monitoring results.

3. Defrosting Platform Implementation

3.1 System Operating Environment

1) Hardware Environment:

- Image Acquisition Device: Hikvision CMOS low-light camera with infrared fill-light, 1920*1080 pixels or above.
- Environmental Monitoring Device: HL8023-MD series fan coil thermostat, supplemented with temperature and humidity controllers, data acquisition cards, industrial computers, and infrared sensors to monitor environmental parameters and provide frost layer thickness reference.

Image Processing Device: The image acquisition and processing program runs on an embedded mini industrial computer. The required configuration is CPU above 3GHz, memory 4GB or above.

Network Environment: This system does not require an internet connection.

2) Software Environment:

Operating System: The embedded mini industrial computer needs Windows 10 or above installed.

Application Software: Python 3.8.1 or above must be installed.

3.2 Defrosting Effectiveness

1) Image Acquisition Effect: Clear heat exchanger surface images can be acquired under different lighting conditions such as nighttime low light, natural light, and strong light. After preprocessing, the contrast between frost and non-frost areas is significantly enhanced, meeting grayscale recognition requirements.

2) Algorithm Performance: In comparative tests between threshold segmentation algorithms and deep learning models, the deep learning model achieved higher recognition accuracy. Single-frame image processing time is ≤ 0.5 s, meeting real-time control requirements.

3) Environmental Adaptability: In simulated extreme conditions of-10℃, 90% humidity, and complete nighttime darkness, the platform, utilizing infrared fill light and low-light enhancement algorithms, can still stably acquire and process images, with a frost recognition error rate ≤ 5%.

4. Conclusion

The “Frost Defrosting Control System for Air-Source Heat Pump Based on Nighttime Adaptive Image Gray-Scale Recognition” directly measures frost layer area and density, combined with multi-parameter dynamic thresholds. Compared to traditional TT, TEPS, and THT methods, this system reduces the false defrosting rate to below 3%, effectively avoiding unnecessary defrosting actions.

The system’s energy efficiency is more optimized. Comparative experiments across multiple climate zones show that, compared to traditional timed defrosting methods, this method reduces the nominal heating capacity loss coefficient and significantly improves the comprehensive energy efficiency ratio for frosting/defrosting cycles, while also reducing compressor wear and extending equipment lifespan.

The system demonstrates strong practicality. The hardware system is low-cost, the software algorithm is easy to integrate, adaptable to multiple scenarios such as residential heating and industrial refrigeration, and capable of adapting to different climate conditions in both northern and southern China, possessing value for engineering promotion.

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