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Research paper

A fault detection method for heat loss in a tyre vulcanization workshop using a dynamic energy consumption model and predictive baselines

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HIGHLIGHTS

- A new fault detection strategy is developed for heat loss in a tyre vulcanization workshop.
- A dynamic and hierarchical energy consumption model is developed for estimating the heat loss.
- The expected energy consumption of the vulcanization process is derived from thermodynamic theory.
- The LMBP algorithm and energy consumption factors are adopted to estimate the baseline for the heat loss.
- The proposed strategy improved detection performance significantly, especially on the faults at low level.

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ABSTRACT

In a tyre vulcanization workshop (TVWS), the faults of steam traps and insulating layers usually lead to great heat loss and significantly lower energy efficiency. These faults tend to be difficult to detect in practice, and hence often got ignored. This paper presents a fault detection method for heat loss at a workshop level. A dynamic and hierarchical energy consumption model (DHECM) for a TVWS is proposed to establish the expected energy consumption of the vulcanizing process from thermodynamic theory. This model allows the separation of the heat loss and the technical energy consumption from the actual energy usage. The LMBP algorithm and energy consumption factors are adopted to estimate the baselines for the heat loss and help detect the faults. This method is validated in a large TVWS in Guangzhou China. Test results show that the heat loss of the TVWS was reasonably evaluated and it accounted for as much as 44.78% of the energy consumption under its regular operations. The heat loss estimation facilitated better detection performance, and helped identify the faults at a low level.

1. Introduction

Vulcanization is the final process in tyre manufacturing where green tyres are formed to the desired shape and converted to strong, elastic material under elevated temperature and pressure [1–3]. It consumes a large amount of steam and causes high cost and environment pollution. Abnormal heat loss in a tyre vulcanization workshop (TVWS) mainly refers to the internal leakage and heat dissipation (IL&HD) respectively caused by the faults of steam traps and insulating layers. According to the reports of our studied tyre plants, a vulcanizer with such faults may consume two to three times more steam than normal, and the steam waste reaches nearly 15% of the total steam consumption every year. Detecting and repairing these faults in time is very important for reducing production cost, security risk and pollution emission.

Modern vulcanizing process is automatically accomplished in a vulcanizer, where a green tyre is fixed between the steam room and the bladder. High pressure steam is injected into the steam room and the bladder and transfers heat to the green tyre. High pressure nitrogen is injected into the bladder and provides pressure. The steam traps connected with the steam room and the bladder are used to timely discharge the condensate. Their

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Nomenclature

Bi	Bolt number
c	material heat ratio
E	energy consumption
Fo	Fourier number
h	specific enthalpy
H_r	the inner height of a tyre (mm)
m	mass (kg)
P	pressure (MPa)
Q	heat absorption or heat release
R_r	the inner radius of a tyre (mm)
t	temperature (°C)
V	volume
W	work

Greek symbols

α	significance level
γ	convection heat transfer coefficient
δ	the half thickness of the tread of a tyre
ε	prediction error
η_r	the designed radial extension ratio of a tyre
θ	surplus temperature
λ	thermal conductivity
μ_1	the characteristic value of discrete surfaces.
ρ	material density,
σ^2	standard deviation
τ	time span (s)

Subscripts

A	ambience or actual energy consumption
BS	boiler steam
C	condensate
CB	changing bladders
CM	changing molds
D	discharged energy
DW	deaerated water
HT	heating tyre in a bladder
i	the ith individual process
IS	inner steam
KP	keeping pressure in a bladder
L	energy loss
N	nitrogen
OS	outer steam
P	physical energy consumption
S	steam
T	technical energy consumption
TR	tyre
V	vulcanization
VE	mold open during a vulcanizing process
w	workshop level

internal leakages tend to make the steam discharged without condensing. The insulating layers covering the steam room are used to prevent heat from dissipating [4]. The IL&HD don't impact production at a low level and tend to be difficult to be detected by observation. Practitioners usually detect the faults by regular manual inspection in practice, but it is time-consuming and inefficient. Some plants even ignore them until huge waste or safety issues happen.

Researchers and practitioners proposed to adjust IL&HD in the scope of the leakage of pipe system, and detect them by analyzing the temperature, pressure, flow rate, vibration and acoustics around the potential leakage points - see Heo and Lee [5], Jinet al. [6], Zhu et al. [7], Zhang [8], Wei et al. [9], Qu et al. [10], Chen and Ye [11], and Qi [12]. These methods can detect the faults in a short time, but their automation has to be supported by a large sensor network which tends to be restricted by the cost and technology in a TVWS. In fact, the IL&HD can be considered as a problem of energy consumption and can be detected by assessing against the theoretical baseline of such consumptions. Researchers proposed to observe energy consumption from multi perspectives as organization, production and technology. Duflou et al. [13] and Reich-Weiser et al. [14] divided it into five levels from organization: device/unit process, line/cell/multi-machine system, facility, multi-factory system and enterprise/global supply chain. Rahimifard et al. [15,16], Wang et al. [17] and Li et al. [18] proposed three levels from perspective of production: process, product and production. Kreitlein et al. [19], Kara and Li. [20], Bi and Wang [21], and Frank et al. [22] presented three levels from perspective of technology: theoretical, technical and real. These works provided comparable indexes and evaluation methods for manufacture energy efficiency. The baselines of the indexes are usually mined from historical data using artificial neural networks [23] and supported vector machines [24], or derived from energy-balances and mass-balances [25,26]. Researches on energy saving of tyre vulcanization still focus on the technology improvement, and hence no other works about fault detection for the IL&HD are found besides our two previous works [27,28]. In the two works, we proposed a non-dynamic energy consumption model for tyre vulcanization at a process level and two evaluation methods for energy efficiency baselines. They can detect the abnormal heat loss if the energy consumption of an individual tyre vulcanizing process (TVP) is available.

Although the existing researches on energy consumption have established theoretical basis, there still exists three difficulties in developing a practical detection method for the IL&HD: the restriction of energy measurements, the fuzziness of heat loss, and the variety of the influence factors of the heat loss. On the first difficulty, the impediment of flow meters tend to strengthen the difficulty in the control of the temperature and pressure of a TVP, and hence only the gross steam consumption is available in most of running TVWS's, and only the establishment of the energy baselines at a workshop level is feasible. On the second difficulty, the heat loss is hidden in the actual energy usage and its dynamic fluctuation cannot be theoretically explained. On the third difficulty, heat loss is influenced by ambience, technology, job schedule, and etc., and the normal mode of heat loss is hard to be accurately derived to distinguish from the abnormal heat loss.

The objective of this paper is to propose a new practical fault detection method for abnormal heat loss (such as IL&HD) based on analyzing the energy consumption. Three innovations are adopted to overcome the above three difficulties. Firstly, we investigated the available measurements in a large TVWS and developed the workshop-oriented detection method to overcome the restriction of energy measurements. Secondly, we proposed a dynamic and hierarchical energy consumption model (DHECM) to overcome the fuzziness of heat loss. This model established the expected energy consumption of the vulcanizing process from thermodynamic theory and allows the separation of the heat loss and the technical