Exergy-based performance degradation diagnosis for use in digital twins of thermal systems

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Agenda

- Introduction
- Scope of the work
- Methodology
- Case study
- Conclusions
In the throttling process energy is conserved, but exergy is destroyed.

\[ p_1 = 20 \text{MPa} \]
\[ T_1 = 500 \degree \text{C} \]
\[ p_2 = 15 \text{MPa} \]
\[ T_2 = 475 \degree \text{C} \]

Energy balance:
\[ h_1 = h_2 \]
\[ 3241 \text{kJ/kg} = 3241 \text{kJ/kg} \]

Exergy balance:
\[ e_D = e_1 - e_2 \]
\[ 343 \text{kJ/kg} = 1443 \text{kJ/kg} - 14100 \text{kJ/kg} \]

In the throttling process energy is conserved, but exergy is destroyed.

Results of applying exergy analysis for the heat pump – the evaporator is the main cause of decreasing energy efficiency.

Energy supply with sources at different quality levels for the space heating and metallurgical processes.
Exergy-based methods for diagnosis:

1. Exergy Cost Theory, thermoeconomic diagnosis (A. Valero and co-workers, University of Zaragoza, Spain).

2. Advanced exergetic analysis (G. Tsatsaronis, T. Morosuk and co-workers, Technische Universität Berlin, Germany, China)

Splitting exergy destruction within the component according to the methodology of the advanced exergetic analysis.
Digital Twin Concept for diagnosis

**Physical system**

- Creating data
- Collecting data
- Data analysis
- Fault detection and diagnosis
- Early stage warning and predictive maintenance

**Virtual system**

- Collecting data
- Data analysis
- Fault detection and diagnosis
- Early stage warning and predictive maintenance
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Platform Level on Clouds

- Simulation Models Run-Time (HTTP Server on Container Python)
- Historical Database (InfluxDB)
- Master Data & Models (IBM Cloudant)
- Analytic Services (Grafana)

Central Twin Subsystem (Node-RED)

On-Location Edge Equipment 1

- IoT Gateway
- Local Twin Data (CouchDB)
- Real Time Twin Subsystem (Node-RED)

On-Location Edge Equipment 2

Industrial Applications

IoT Gateway

- Interfaces (Ethernet, Serial, GPIO, etc)
- Model
- I/O Data

Industrial Control System

- Model Data
- I/O Data
- I/O Data, Commands

Sensors/Actuators

Physical Entity

On-Location Edge

- Data, Models, Config (Sync)
1. pip install CoolProp
2. Collecting CoolProp
3. Downloading CoolProp-6.4.1-cp37-cp37m-manylinux1_x86_64.whl (4.2 MB)
4. Installing collected packages: CoolProp
5. Successfully installed CoolProp-6.4.1

135 e_2_H_Des = T_0 * (s_0 - s_2_Des_0) - (h_0 - h_2_Des_0)
136 # Specific thermal exergy of the working fluid at the compressor
137 e_2_T_Des = (h_2_Des - h_2_Des_0) - T_0 * (s_2_Des - s_2_Des_0)
138 # Heat rejection in the condenser
139 q_out_Des = h_2_Des - h_3_Des
140 # Heat addition in the evaporator
141 q_In_Des = h_1_Des - h_4_Des
142 # Coefficient of performance of the heat pump
143 COP_Des = q_out_Des / l_CM_Des
144 # Mass flow rate of the working fluid
145 m_wf_Des = Q_HP_Des / q_out_Des
146 # Total heat addition in the evaporator
147 Q_in_Des = q_in_Des * m_wf_Des
148 # Total heat rejection in the condenser
149 Q_out_Des = q_out_Des * m_wf_Des
150 # Total power consumption of the compressor
151 N_Des = 1_CM_Des * m_wf_Des
152 # Mass flow rate heat source fluid
153 m_EV_h_Des = Q_in_Des / (h_EV_h_in_Des - h_EV_h_out_Des)
154 # Mass rate heat consumption fluid
155 m_CD_c_Des = Q_out_Des / (h_CD_c_out_Des - h_CD_c_in_Des)

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1. # Title Calculation of parameters of low temperature and consumer
2. if wf_EV_h == 'Air':
3. h_EV_h_in_Des = airHTP(T_EV_h_in, p_EV_in, phi_0)
4. if wf_EV_h == 'Water':
5. h_EV_h_in_Des = HPT(p_EV_in, T_EV_h_in, wf_EV_h)
6. if wf_EV_h == 'Air':
7. h_EV_h_in_Des_0 = airHTP(T_0, p_EV_in, phi_0)
8. if wf_EV_h == 'Water':
9. h_EV_h_in_Des = HPT(p_EV_in, T_0, wf_EV_h)
10. if wf_EV_h == 'Air':
11. s_EV_h_in_Des = airSTP(T_EV_h_in, p_EV_in, phi_0)
12. if wf_EV_h == 'Water':
13. s_EV_h_in_Des = SPT(p_EV_in, T_EV_h_in, wf_EV_h)
14. if wf_EV_h == 'Air':
15. s_EV_h_in_Des_0 = airSTP(T_0, p_EV_in, phi_0)
16. if wf_EV_h == 'Water':
17. s_EV_h_in_Des = SPT(p_EV_in, T_0, wf_EV_h)

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Q-T Diagram of the evaporator

T-s Diagram of the heat pump
Results during performance degradation process
Conclusions:

1. The work proposes application digital twinning and advanced exergy-based analysis for determining the anomalies and quantifying their negative impacts in thermal systems.

2. A prototype of a digital twin for the thermal system with a structure, contents, programming tools for data processing, storage, transferring, model-based analysis and displaying has been developed.

3. The implementation of a heat pump digital twin is performed. The case of simultaneous malfunctions due to fouling within the both the evaporator and condenser is investigated.

4. On the base of operation conditions of the investigated heat pump it has been shown that in case of fouling providing similar temperature differences within the heat exchangers the evaporator has higher priority for cleaning or replacing compared to the condenser.
Thank you for your attention