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Generalized predictive control applied in waste heat recovery power plants

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HIGHLIGHTS

- ▶ The generalized predictive control approach is applied for a waste heat recovery process with organic Rankine cycle.
- ▶ The design procedure of the generalized predictive controller is presented.
- ▶ Simulation tests show the tracking ability and the disturbance rejecting performance of this controller.

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ABSTRACT

A multivariable control strategy is needed to ensure high efficiency and load-following capability in the operation of waste heat recovery power plants. In this paper, a generalized predictive controller is proposed for a waste heat recovery process operating on an organic Rankine cycle. The simulation results show that the proposed control strategy not only can achieve good transient and steady response along with decoupling performance, but also can obtain satisfactory disturbance rejection performance.

1. Introduction

In recent years, more attention has been paid to saving energy and alleviating environmental problems [1–4]. In particular, interest in low-grade waste heat recovery has grown dramatically in the past decades. Organic Rankine cycle (ORC) systems are ideal candidate for recovering low grade heat. ORC is capable of generating more power from low grade heat sources by using organic working fluids which have a higher vapour pressure than water, moreover, the advantages of ORC also include economical utilization energy resources, reduced emissions of CO, CO_2, NO_x and other atmospheric pollutants, simplicity and commonly available components. Therefore, ORC has been widely applied in practice, such as industrial waste heat recovery, solar thermal power systems, binary geothermal power plants, solar ORC–RO desalination systems, duplex-Rankine cooling system, ocean thermal energy conversion systems and biomass-based power generation systems [1,2,5].

Considerable studies have been conducted on ORC systems in previous works, e.g., selection of organic working fluid [6–8]; expander integrated into ORC systems [9–11]; process integration of ORC [12]; operation optimization of ORC heat recovery power plants [13]; performance analysis and optimization of ORC systems [14–20].

To our best knowledge, very few publications have focused on control of ORC systems. When load demand changes or the waste heat sources are disturbed, it is necessary to control the ORC process in order to keep the key operating parameters within allowable ranges. The PI control strategy of ORC systems was investigated in [21]. The evaporating temperature was controlled by manipulating the expander speed, while the superheating was controlled by the pump flow rate. The PI controller used in each control loop can be easily tuned and implemented [22], however, it is difficult to adaptively tune proper PI parameters in ORC processes owing to multivariate coupling, variant operating condition and disturbances. In [23], a multivariable control strategy for an ORC based waste heat recovery system was proposed by incorporating a linear quadratic regulator (LQR) with a PI controller, however, this control algorithm needs an accurate linear state space model of the ORC process. Although the proposed method can achieve satisfactory control performance for the ORC process around a nominal operating condition, however, the control performance will degrade in presence of varying operating conditions or strong disturbances.

The dynamics of ORC processes was investigated in [23], it is clear from the established physical model that the ORC based waste heat recovery power plant is a complex process characterized by nonlinearity, uncertainty, multivariable coupling and load

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disturbance. Therefore, such processes cannot be described by simple equations with constant parameters. Although a control-oriented nonlinear model was built for ORC processes in [23], it is still necessary to develop a properly simplified model with variable coefficients so as to design simple and easily implemented controllers for ORC processes. In this paper, the Controlled Auto-Regressive Integrated Moving Average (CARIMA) model will be adopted to model the ORC based waste heat recovery power plant, the well-known recursive least squares method with forgetting factor will be used to identify the model parameters in real time.

Generalized predictive control (GPC) strategy is easy to understand and implement, this model based predictive control method has been widely applied in industrial processes due to its effectiveness in the control of multivariable systems with strong interactions, disturbances and operating constraints [24–30]. A set of optimal future control signals are solved by minimizing a cost function which is defined based on future output errors and control inputs.

The objective of this paper is to develop an adaptive GPC for waste heat recovery power plants with ORCs. The reminder of this paper is organized as follows: Section 2 describes the ORC based waste heat recovery power plant. The main control objects of the waste heat utilizing process are then investigated. Section 3 develops GPC algorithm for waste heat recovery power plants. Section 4 presents the simulation results to illustrate the efficiency and feasibility of the proposed approach. Finally, several conclusions are drawn in Section 5.

2. Process description

The schematic diagram of the investigated 100 kW waste heat recovery power plant is shown in Fig. 1. Organic Rankine cycle is utilized to generate electric power from waste heat in this power plant. R245fa whose critical properties listed in Table 1 is selected as working fluid in this ORC. The flue gas waste heat is transferred to the evaporator where working fluid R245fa is heated before it enters a turbine expander, the vaporized R245fa drives the expander for power generation. The vapor from the expander is then condensed into liquid state in an air-cooled condenser. The liquid is pressurized by the pump and sent back to the evaporator.

In order to ensure that the ORC process operates with high efficiency and load-following capabilities, the control system for a waste heat recovery power plant usually needs to meet the following requirements:

(1) Electric power output must be able to follow the demand from power grid.

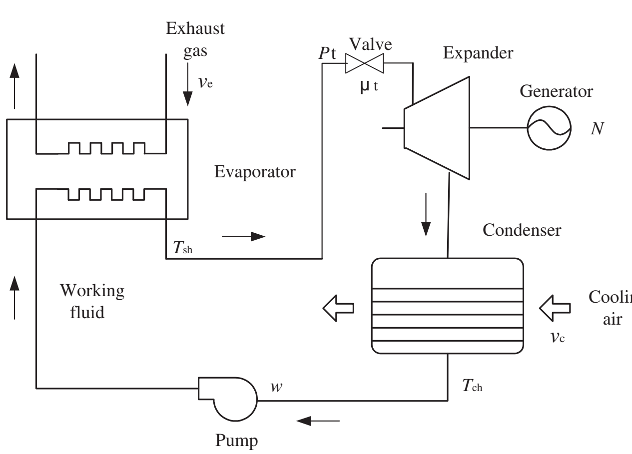

Fig. 1. The schematic diagram of the ORC system.

Table 1
Critical properties of R245fa.

Molecular formula	$CF_3CH_2CHF_2$
Molecular weight	134.05 g/mol
Critical pressure	3640 kPa
Critical temperature	427.20 K
Critical density	517.0 kg/m^3

(2) Throttle pressure at the inlet of expander must be maintained despite variations of the load. Throttle pressure stands for energy balance between energy supply from evaporator and energy needs from turbine expander, which is similar to boiler-turbine unit in power plants [31].

(3) The superheated vapor temperature at the outlet of the evaporator must be maintained at a desired level. The temperature of working fluid at the outlet of evaporator could not exceed the critical temperature of working fluid to prevent its decomposition and deterioration [20]. Moreover, the temperature of the working fluid at the outlet of evaporator could not exceed the specified lower bound in order to prevent wet vapor from entering turbine expanders.

(4) The temperature of working fluid at outlet of condenser must be maintained at a desired level to ensure high efficiency of ORC. It was pointed out that the sub-cooling should be maintained at 0.5 – 0.6 °C in order to achieve best performance for ORC systems [20].

The controlled variables and manipulated variables are listed in Table 2. Denote the manipulating input vector and output vector as $u = [u_1, u_2, u_3, u_4]^T$ and $y = [y_1, y_2, y_3, y_4]^T$ respectively. The main objectives of the waste heat utilizing process control problem are therefore to control the output vector $y = [y_1, y_2, y_3, y_4]^T$ by manipulating input vector $u = [u_1, u_2, u_3, u_4]^T$.

3. GPC design for ORC systems

The GPC strategy for the waste heat recovery power plant is shown in Fig. 2. GPC is a model-based strategy in order to maintain the outputs of the controlled plant close to their desired set-points. The future outputs for the prediction horizon are predicted at each instant based on the waste heat utilizing process model, accordingly, the optimal control action is calculated by solving an optimization problem at each sampling interval so as to keep each measured process output y_i $(i = 1, 2 \ldots 4)$ as close as possible to its set-point y_{ir} $(i = 1, 2 \ldots 4)$.

Although the use of nonlinear model in the predictive control of waste heat recover power plant probably can obtain better performance than the use of linear models, however, it suffers from some problems, for example, the use of nonlinear models may lead to a non-convex optimization problem. In addition, it is difficult to

Table 2
Controlled and manipulated variables.

Descriptions	
Controlled variables	
y_1	N power output (kW)
y_2	P_t throttle pressure (kPa)
y_3	T_{sh} superheated vapor temperature at the outlet of evaporator (°C)
y_4	T_{ch} working fluid temperature at the outlet of condenser (°C)
Manipulated variables	
u_1	μ_t throttle valve position (%)
u_2	w pump speed (r/min)
u_3	v_e exhaust velocity (m/s)
u_4	v_c air velocity (m/s)