Applied Thermal Engineering 106 (2016) 117–124

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Temperature control for a vehicle climate chamber using chilled water system

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HIGHLIGHTS

- Cooling loads under typical test conditions were analyzed.
- Equal percentage valves were used for the chilled water system.
- Fuzzy PID was designed for control of adjusting valves and electrical heaters.
- Performances of PID and fuzzy PID were predicted using Matlab/simulink.
- Settling time and temperature errors were largely reduced with fuzzy inference.

ARTICLE INFO

Article history:
Received 25 February 2016
Revised 6 April 2016
Accepted 28 May 2016
Available online 31 May 2016

Keywords:
Chilled water system
Valve selection
Temperature control
Fuzzy PID

ABSTRACT

The effective temperature control of a vehicle climate chamber was investigated. The temperature was regulated by electrical heater power and valve opening in the chilled water system. Cooling load and water flow rate through the adjusting valve were studied based on the distributed parameter model developed in a previous article. In order to ensure the flow capacity and increase linearity between the cooling side control output and the air temperature, two equal percentage valves were applied. The climate chamber has characteristics of large thermal inertia and non-linearity. Performance of a proportional–integral–derivative (PID) controller used in the existing system was not satisfactory, so a fuzzy self-tuning PID controller was designed. The PID gains were tuned online according to temperature error, error change rate, and air velocity using fuzzy logic. Model predictions showed that the fuzzy PID control stabilized the air temperature in a shorter time and with smaller overshoot and undershoot. The time averaged temperature error was reduced from 0.37 °C to 0.09 °C in the high temperature test, and that of the low temperature test was reduced from 0.42 °C to 0.18 °C.

1. Introduction

Effective and accurate testing is indispensable for the research and development of cars. Engineers need to validate vehicles under harsh weather conditions such as high temperature and humidity which are common along the Gulf Coast, or extreme low temperatures typical of colder regions. Using a climate chamber to provide a controlled environment can shorten the time from development to product launch, so car manufacturers can be less dependent on field tests, which reduces the cost and minimizes the safety risk associated with public road tests. Over 20 kinds of tests can be conducted in a climate chamber including hot and cold start tests, brake system test, fuel efficiency analysis, exhaust emission analysis, windshield defrost/demist test, durability, and structural assessment. So vehicle climate chamber has become essential equipment for automobile testing.

A vehicle climate chamber should be able to simulate a wide range of weather conditions, so the ranges of temperature and air velocity duplicated are important. Additionally, other technical indexes are used to assess the quality of the climate chamber, such as the uniformity of air velocity at the outlet of nozzle, uniformity of solar radiation density in the test area, and the wind speed in front of the test vehicle for the idle test. However, as a thermal system test apparatus, temperature controllability and stability are the primary concern. Air temperature control is crucial to assure the accuracy of test results. Controlled temperature in the test section should remain within the error band during the test, and the temperature error should be minimized. Requirements

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http://dx.doi.org/10.1016/j.applthermaleng.2016.05.168
1359-4311/

Nomenclature

C_v	valve coefficient
C_p	specific heat capacity at constant pressure, J/(kg K)
D	derivative time, s
e	scaled temperature error
$\dot{e}$	derived change in error
h_{petrol}	low calorific of petrol
I	integral time, s
K_v	valve gain
K_P	proportional gain
P	power, W
q_v	volume flow rate, m^3/h
qm	mass flow rate, kg/s
Q	cooling load, W
S	oil consumption, kg/s
t	time, s
ts	sample time, s
T	temperature, °C
u	control output, %
V_a	air velocity, m/s

Greek symbols

α	valve opening, %
Δp_{valve}	valve pressure drop, 100 kPa
ρ	density, kg/m^3
ϕ	solar radiation intensity, W/m^2

Subscript

a	air
b	back water
C	cooling side
H	heating side
m	measured
r	reference
s	supply water
w	chilled water

for climate chamber air temperature control are listed in Table 1. There are different methods for temperature regulation of climate chambers. The use of a chilled water system allows easy control, and shows high precision and flexibility compared to the vapor-compression refrigeration system. For this reason, chilled water systems are commonly used in industrial, commercial, and domestic buildings, and is also recommended for temperature regulation in climate chamber. Previous studies found that energy performance can be improved by the optimization of the design or control of chilled water systems [1–4].

Building temperature control has drawn increased attention in recent years, partly due to a growing emphasis on thermal comfort and energy saving. PID controller use a control loop feedback mechanism and are commonly used to regulate industrial systems. As the performance of these PID controllers may be less than optimal, lots of advanced control methodologies have been proposed, such as model predictive control. It is considered as a good way to lower costs by making adjustments based on information such as the weather forecast, occupancy schedule, or electricity price [5,6]. However, model predictive control prefers a linear low order model [7]. The thermal system of a climate chamber includes many factors, and has variables that change with time and also has unmeasured disturbance sources, so it is difficult to construct a simple identified model. Other approaches have been proposed are fuzzy logic [8–10] and artificial intelligence [11,12].

Of these approaches, fuzzy PID control is a promising solution which allows implementing the optimization even to an existing PID control system. Gain scheduling in fuzzy PID has been proved as an effective way to overcome the nonlinear characteristics of controlled system [13]. Blanchett and Kember studied the fuzzy input variable and provided ways to reduce the redundancy of rule bases [14]. Bin et al. used a fuzzy PID strategy for a large hydraulic system and showed that it can efficiently improve the control accuracy, irrespective of time delay and parameter variations [15]. Fuzzy adaptive controllers have also been successfully used for HVAC systems [16,17]. However, fuzzy control depends on system dynamics, so focused research needs to be performed for each specific system to be controlled in order to obtain an optimal set of control rules. Furthermore, control systems rely on actuators to act upon the controlled environment and these actuators must be chosen according to the process conditions. Inappropriate actuators can eliminate the effectiveness of process control, but this has not been well-studied.

Table 1
Technical specifications required for temperature control of the vehicle climate chamber.

Specification	Requirement
Temperature control range, °C	−25 to 60
Temperature control tolerance, °C	Within ±1
Overshoot/undershoot of T_a, %	⩽5
Heating rate, °C/min	⩾0.2
Cooling rate, °C/min	⩾0.15

In our previous article [18], we developed a transient thermal model for an existing vehicle climate chamber using a distributed parameter method. The model consists of a chilled water system, air, and climate chamber envelope, and was validated by test data. In this study, the steady and dynamic responses of vehicle climate chamber were further analyzed using the model. The results were used for valve selection for the chilled water system and facilitated design of a new controller. Simulations showed the newly designed fuzzy self-tuning PID controller exhibits better performance compared to that of the classical PID controller.

2. Valve selection

A schematic diagram of the vehicle climate chamber is shown in Fig. 1. During operation, the centrifugal fan runs to drive a high speed airflow, allowing air to circulate inside the tunnel. The solar simulation system provides the required solar radiation. The exhaust device removes the exhaust created by the test vehicle to prevent the pollution of the air inside the chamber. The chilled water system employs a primary-secondary pumping arrangement. Water is cooled down in the refrigeration unit and adjusting valves can regulate the water flow rate into the secondary pump side. Electrical heaters were installed in the secondary pump side. Air temperature at the outlet of the nozzle is measured using a thermocouple and transmitted to controller (indicated by the dashed line). The controller implements the control algorithm and outputs two control signals, one for the power of the electrical heater and the other for valve opening.

2.1. Calculation of flow rate though the valve

Control valves are imperative elements allowing regulation of fluid flow. The performance of the adjusting valve is crucial to