DEVELOPMENT OF AN OPTIMIZATION CONTROL SYSTEM FOR A CONTINUOUS REHEATING FURNACE IN WHICH EQUATRAN-G IS UTILIZED

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Modeling and simulation technology is one of the key factors in the development of operation support systems, operation training simulators and advanced control systems. EQUATRAN-G, an all-purpose equation solver, enables the calculation of various types of mathematical models by simply describing equations. Therefore, it is possible to create dynamic models for these systems efficiently. This article describes the functions of EQUATRAN-G and gives an actual example of the utilization of EQUATRAN-G in an optimization control system for process modeling.

INTRODUCTION

Dynamic simulation technology has come to play a very important role in achieving efficient and optimal plant operations. There are three principal systems, as outlined below, for which a dynamic simulator is used.

- Off-line System
  In this system, the dynamic simulator is used in off-line mode to examine and improve the operation and control strategies for new and existing plants, develop and inspect advanced control systems, and for other purposes.

- Quasi-online System
  In this system, the dynamic simulator is used in quasi-online mode to develop and inspect operation training simulators, DCS control logics and plant diagnosis systems, train process/control engineers and operators, and for other purposes.

- Online System
  In this system, the dynamic simulator is used in online mode to support operations based on predictive simulation, optimize conditions during dynamic operations that occur at continuous process plants, and for other purposes.

In any mode of use, the key issue is how to create a model for simulating process behaviors and perform numerical calculations.

The EQUATRAN-G equation solver introduced in this article allows for building and computing models using formulas without requiring programming. To this effect the solver may be called a “script language for numerical calculations.”

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Figure 1  Problem Solving Procedures
As an example of EQUATRAN-G applications, we will discuss our development of a control system in the High Performance Industrial Furnace Development Project that was entrusted with the Japan Industrial Furnace Manufacturers Association by the New Energy and Industrial Technology Development Organization (NEDO).

INTRODUCING EQUATRAN-G

EQUATRAN-G vs. Other Programming Languages

In this section, we will explain how EQUATRAN-G differs from other programming languages. Figure 1 shows the different approaches of EQUATRAN-G and FORTRAN/BASIC to problem solving procedures. The procedure on the left is typical to programming languages such as FORTRAN and BASIC. First, mathematical models are created, followed by the development of calculation procedures, namely algorithms; essential to this step is knowledge of calculation methods for linear, non-linear equations and ordinary differential equations (e.g., ordinary differential equations employ the Runge-Kutta method). To ensure calculations are accurately performed, programming is performed and errors are corrected (debugging) in accordance with the algorithms. This process not only requires a substantial amount of time and effort, but also knowledge of syntax and programming is vital.

In contrast, EQUATRAN-G does not involve complex procedures as both programming and debugging are performed automatically. This allows engineers to focus on their actual work.

FUNCTIONS OF EQUATRAN-G

Next, we will take a look at the functions of EQUATRAN-G.

(1) Equation Solving Functions

EQUATRAN-G can perform numerical calculations of simultaneous linear and non-linear equations, ordinary differential equations including high-order and non-linear types, optimization and least-squares methods such as non-linear equations. Equations can be entered in any order, and there is no need to modify or transpose them. Automatic selection and application of calculation procedures are performed.

It allows for the direct entering of linear and non-linear simultaneous equations. Generally, a solution to simultaneous non-linear equations requires, for example, the iterative method. EQUATRAN-G can determine whether the simultaneous equations are linear or non-linear and choose a calculation method to solve them. Instead, users may select an iterative calculation method. With ordinary differential equations, the high-order equations can be written by simply describing one statement that specifies integral calculations, and this is done without having to modify the equations. Independent and evaluation variables are specified for optimization calculations.

EQUATRAN is also useful for solving compound-complex problems with a combination of ordinary differential equations and linear/non-linear equations, simultaneous non-linear equations involved in the calculation of an optimization problems, etc. More complex problems, such as multiple integrals, two-point boundaries value and mini-max problems, parameter identification in dynamic simulation, can be solved with user-defined functions.

(2) Model Descriptions

EQUATRAN-G features a variety of functions for easy model descriptions, as described below:

- Array Variables: Uses one and two-dimensional array variables.
- Built-in Functions: Incorporates thirty-six different kinds of functions, including logarithmic, trigonometric and exponential functions.
- Tables: A TABLE statement is used to define a diagram or a table given to show the relationships between variables, which are described in equations like a function.
- Conditional Equations: Allows for the description of equations where expressions on the right side change depending on certain conditions.
- User Functions and Macros: Provides modules for the description of large-scale models.

(3) Graphing and Report-creating Functions

A variety of graphing functions are available for use in the science and technology field including semi-logarithmic and
logarithmic scale graphs, interpolation by spline curves, curve-fitting by linear, quadratic and cubic equations, etc. Graphs are easily created by the AutoSetup function, and data can be clearly and concisely displayed on a graph by employing makeup functions. Reports can be easily created since calculation results can be represented in the report-form text where data can be entered in any format.

APPLICATION EXAMPLES

As an application example, let us introduce a control system for achieving on-time heating (online schedule free heating) that was developed using EQUATRAN-G. The following outlines the configuration of the control system and models used by the system. Test results obtained by applying the system to an experimental furnace are also shown.

What Is Schedule Free Heating?

“Schedule Free Heating” refers to a heating method that meets the requirements for changing operating conditions, including the targeted outlet slab temperature and soaking level, at certain points of time, in a continuous furnace such as the one shown in Figure 2. Additionally, the control system that achieves Schedule Free Heating by solving the optimization problem, such as minimizing the difference between the preset and actual temperatures in real time, is called the “Optimal Control System for Online Schedule Free Heating.”

Function Blocks

Figure 3 shows the function blocks contained in the control system. In the figure, we developed the optimal online heat pattern calculation function and online tracking function using EQUATRAN-G. The following are the details of each function.

(1) Online Tracking Function

The online tracking function estimates data that cannot be measured directly (temperature distributions inside heated slabs and furnace walls) among a set of data necessary for the control system in the continuous heating furnace. More specifically, this function estimates and computes the current temperature distribution through the giving of measurable data (furnace temperature, air-fuel ratio, etc.) and the past temperature distribution to the online model. The function corrects its estimation by using process data if it is possible to measure part of the temperature distribution with thermocouples or radiation thermometers.

(2) Optimal Online Heat Pattern Calculation Function

The optimal online heat pattern calculation function is the core function of the control system. This function calculates optimization problems in every control cycle by 1) first postulating future patterns of furnace temperatures as a first-order lag function by setting values in every control cycle, and then 2) predicting the outlet slab temperature by giving the postulated heat patterns to the online model. The first-cycle setpoint is given from the group of setpoints at certain intervals obtained by solving the optimization problems, to the interface function as the optimal setpoint.

(3) Interface Function

From the continuous heating furnace, the interface function gathers information, such as slab and furnace temperatures, necessary for the online model of the online tracking function at fixed intervals. Additionally, the function gives the optimal setpoints obtained from the optimal online heat pattern calculation function, at fixed control cycles, to the furnace temperature control function.

(4) Furnace Temperature Control Function

The furnace temperature control function determines the amount of fuel feed needed to obtain the optimal furnace temperature. In practice, this was done using the DCS function.

(5) Operation and Monitoring Panels

Operation and monitoring panels are used to start and stop the functions of the control system and view the system conditions.

Online Model

The optimal online heat pattern calculation function and online tracking function of the function blocks of the control system discussed earlier have common online-operating models of control objects. The following outlines the structure of the
(1) Heat Balance of Furnace Gas
For this object, the non-equilibrium portion of heat balance in furnace gas is calculated to determine an enthalpimetric change in the furnace gas. The radiation heat flux is calculated using the overall heat absorptance ($\Phi_{CG}$) method.

(2) Slab Heat Transfer
For this object, the slab temperature distribution is calculated by dividing the distribution in the depth direction and using the calculus of finite differences. The temperature distribution in the forward direction is calculated separately, slab by slab. It is assumed that there is radiation heat transfer and convection heat transfer from the furnace on the sides in contact with the gas, as well as a specific amount of heat loss on the bottom side.

(3) Furnace Wall Heat Transfer
The furnace walls and ceiling are handled as a group in heat transfer calculation. As with slabs, the temperature distribution is divided in the depth direction and calculated using the calculus of finite differences.

(4) Movement of Slabs
Calculation of a model is performed at a given time interval. With calculation for a duration of movement as much as the width of a mesh in the forward direction, from the moving speed, the object of slab temperature calculation is switched in the forward direction to the next mesh.

(5) Others
It is assumed that air-fuel ratio control and furnace pressure control are performed perfectly. In addition, any momentary behavior of the model resulting from burner operation is ignored.

System Development Using EQUATRAN-G
The online model discussed in Section 3.3 can be described using non-linear simultaneous ordinary differential equations (see REFERENCES (1) for details). The calculation algorithms of the optimal online heat pattern calculation function and online tracking function are completely different from each other, even though the two functions share the same online model. This is because the functions have different purposes; the optimal online heat pattern calculation function is for control and the online tracking function is for estimation (Figure 4).

Accordingly, if this control system is developed using a programming language, two programs with totally different algorithms must be created. This would require an extraordinary amount of labor, including debugging.

By using EQUATRAN-G in this system development, we were able to develop the two aforementioned functions using exactly the same source file for the model. As well as the successful shortening of the turnaround time, great effects were realized with this strategy during trial-and-error case studies.

Experiment Results
Figure 5 shows variations in the practical process data values in relation to changes in the operating conditions (outlet slab temperature setpoint) when the control system was applied to an experimental furnace (dimensions = 4.0 (W) × 3.0 (H) × 8.0 (D) (mm); number of zones = 2; heat of combustion = $400 \times 10^4$ kcal/h).

Although the accuracy of the model remains an issue, we were able to obtain the expected control response, as shown in the figure.

CONCLUSION
With the EQUATRAN-G equation solver, it is possible to easily create a variety of dynamic models (see REFERENCES (2) for details). The software is especially useful when developing a control system based on such a model as the one discussed in Section, “Application Examples.” By simply specifying the input and output of source files, users can create both an online model to be built in the control system and an online model for...
estimation purposes. Thus, users can expect great labor savings in developing control systems.

We expect that as a model creation language for dynamic simulation, EQUATRAN-G will find an even wider range of applications in the area of real-time systems, such as process control computers and training simulators.

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REFERENCES


*3 EQUATRAN-G is a registered trademark of Mitsui Chemicals Inc.