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A finite element simulation system for ceramic drying processes

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A finite-element simulation system for analyzing the ceramic drying process is developed. This system consists of 3 parts : pre-processor, analyzer, and post-processor. The pre-processor creates 3-dimensional ceramics, makes finite-element models, and prepares input for the analyzer. The analyzer computes temperature, moisture content, residual stress, displacement, etc. during the drying process using the information from the finite-element model, material properties, and boundary conditions provided by the pre-processor. In the post-processor, the analyzer's results are visualized to help designer's evaluation of the drying of the ceramic.

Key words: Ceramic drying process, Finite-element simulation, Pre-processor, Post-processor, Analyzer.

Introduction

Recently, simulation has been generalized to replace the real experiment because laborious experimental studies cost a great deal and expensive experiments require high technology and efficiency. Simulation is the expanded notion of computer simulation, in which the problems are easily solved since they are handled virtually. Also, simulation saves a lot of expense and time needed for solving difficult problems and improves various technical functions required to become more accurate and more efficient. Simulation systems are generally accomplish these strong points by performing in turn modeling, pre-processing, calculation, analysis, post-processing, and evaluation.

This study introduces all functional modules employed in the finite-element simulation system for ceramic drying processes. Figure 1 shows the work flow among functional modules in the simulation system and Fig. 2 illustrates a ceramic electric insulator taken as an example in the introduction of the simulation system. Only the hatched part is analyzed because of the axisymmetric shape and the periodic boundary conditions. After modeling the electric insulator with finite-elements in a pre-processor module and specifying the boundary conditions, the initial temperature and moisture content, material properties, and analysis time in the pre-processor interface module, the simulation is performed in the analyzer module. The time histories of analysis results such as temperature, moisture content, principal residual stress, and deforming shape are shown in the post-processor interface module to convert to post-processor data. Finally, the analysis results are visualized in the post-processor.

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Pre-Processor

Overview

The pre-processor makes the analysis model to generate the information on the geometry of the ceramic, maintains the interface with the CAD system, and specifies the analysis conditions. The pre-processor interface module defines the information on the initial conditions, namely initial temperature and moisture content, boundary conditions, material properties, analysis time, etc., which are needed in the analyzer. HYPERMESH, which is one of the pre-processing programs, models quickly the finite-element mesh of the green ceramic based on the input data the designer supplies. HYPERMESH enables one to generate the finite element mesh at high speed and simplifies the course of the modeling for a complex geometry. Also, it is very convenient to use because HYPERMESH has GUI menu for the users.

Pre-Processor Interface Module

The pre-processor interface module largely consists of 9 kinds of menu. In Fig. 3, the control variable menu to include the number of nodes per element, degrees of freedom per node, and number of element sides exposed to the free flow fluid is seen. The initial/ambient menu shown in Fig. 4 involves the initial temperature and moisture content of the material, temperature and moisture content of the external fluid, convective heat-transfer coefficient, and convective moisture-transfer coefficient. The matid menu, which is an interactive input of the parameters concerning material properties,

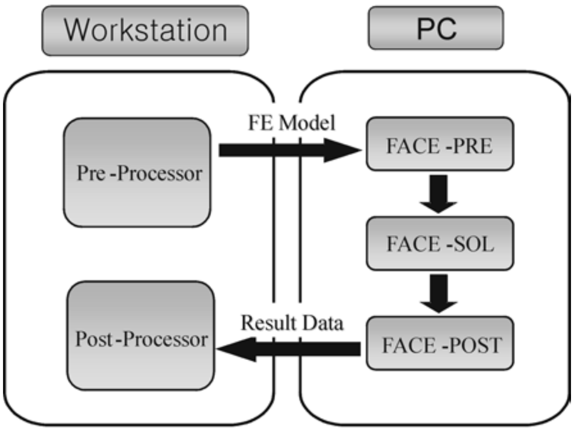

Fig. 1. Work flow of the finite element simulation system for ceramic drying processes.

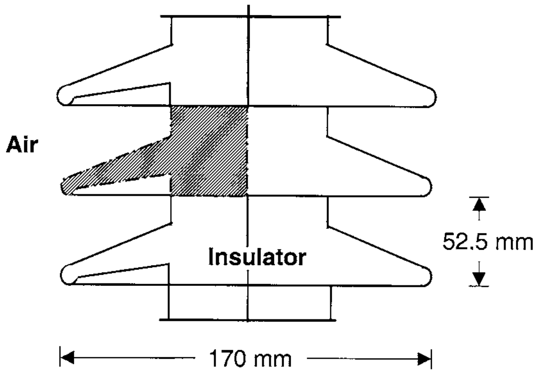

Fig. 2. Schematic view of ceramic electric insulator.

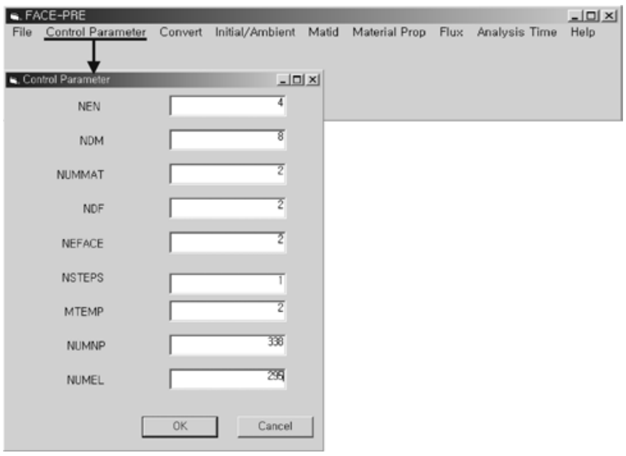

Fig. 3. Control parameter menu in pre-processor interface module.

is listed in Fig. 5, 6 shows the heat property menu specifying the heat property characteristics of the material like heat capacity, thermal conductivity, moisture diffusion coefficient, etc. The flux menu of Fig. 7 is used for considering a convective boundary condition, which is consisted of the input data to define the element side exposed by the boundaries. The analysis time menu seen in Fig. 8 is for assigning the variables associated with the analysis time. The convert

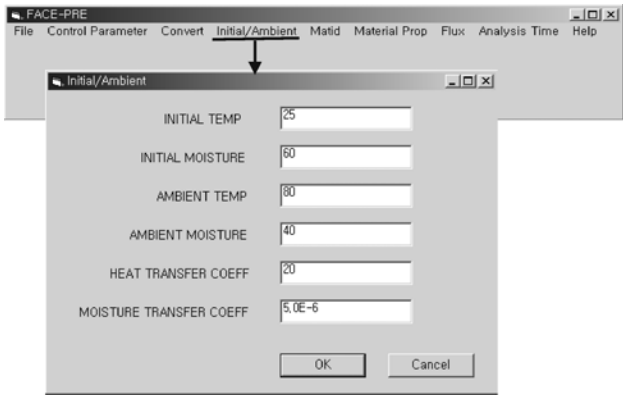

Fig. 4. Initial/ambient menu in pre-processor interface module.

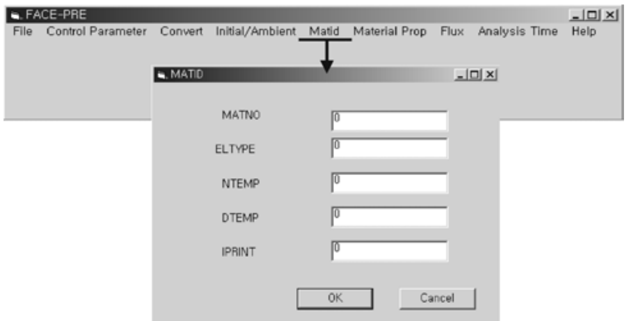

Fig. 5. Matid menu in pre-processor interface module.

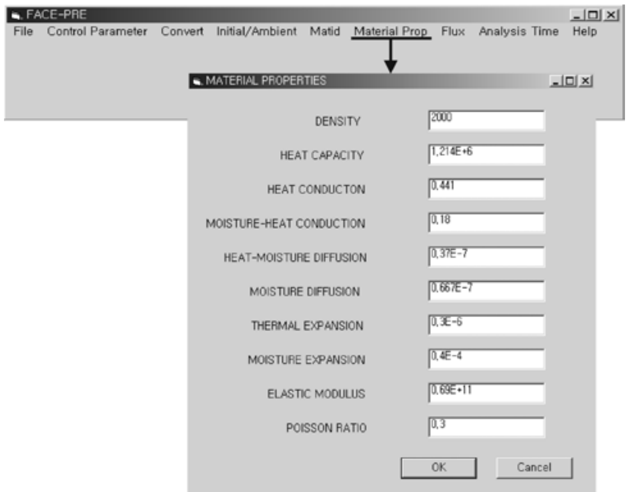

Fig. 6. Material property menu in pre-processor interface module.

menu creates the input data file to use in the analyzer. Figure 9 is a window of the convert menu assigning the input data created.

HYPERMESH

HYPERMESH, which operates in workstation computer, is a finite-element pre-processor highly efficient at visualizing the finite element model of the ceramic. It increases the productivity because the designer can reduce the expense in preparing a complex 3-dimensional finite-element model. Figure 10 shows the finite-

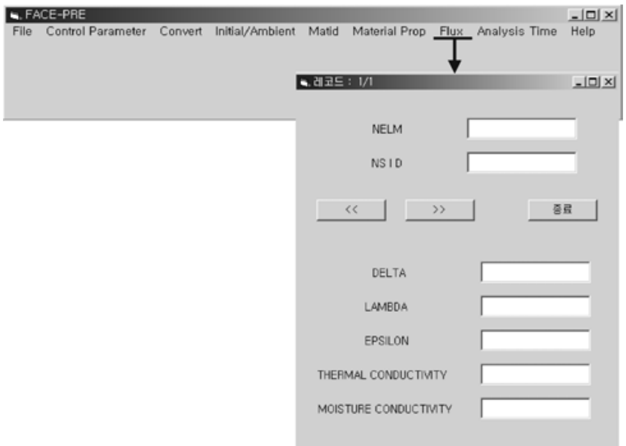

Fig. 7. Flux menu in pre-processor interface module.

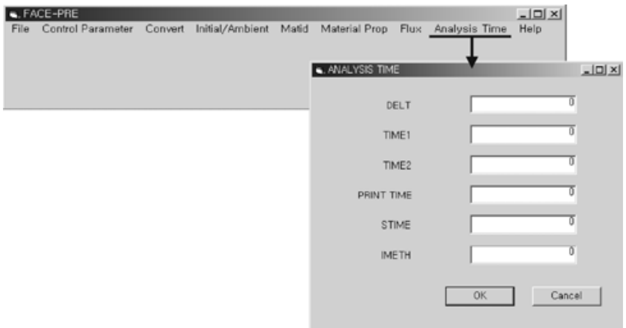

Fig. 8. Analysis time menu in pre-processor interface module.

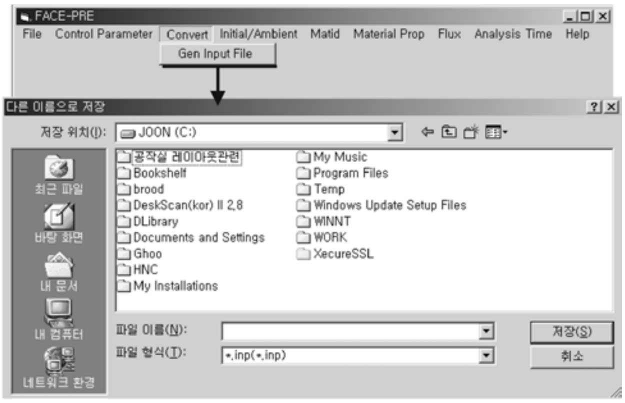

Fig. 9. Convert menu in pre-processor interface module.

element model of a ceramic electric insulator generated from HYPERMESH. The finite-element model has 290 nodes and 248 elements.

Analyzer

Overview

In order to analyze the drying process of the ceramic, the analysis module called "analyzer" is developed. The analyzer, which is written in the FORTRAN language, is able to analyze temperature distribution, moisture distribution, deformed shape, and stress distribution

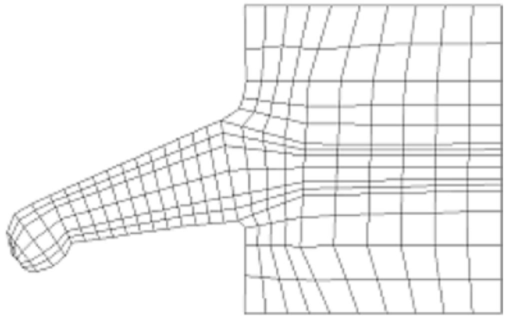

Fig. 10. Finite element model of a ceramic electric insulator.

during the drying process of the green ceramic. The analyzer uses the finite-element mesh, material properties, boundary and initial conditions, and analysis time and analyzes the heat and moisture transfer as well as the structural deformation. The analyzer is divided into 2 parts: temperature-moisture analysis, MAINDI, and deformation-stress analysis, MAINST. In MAINDI, the temperature and moisture distributions are obtained using the initial conditions and the boundary conditions specified as a function of time and position. For the principle stress distribution and deformation of the ceramic during the drying processes, the temperature and moisture distributions computed in the temperature-moisture analysis are used in the deformation-stress

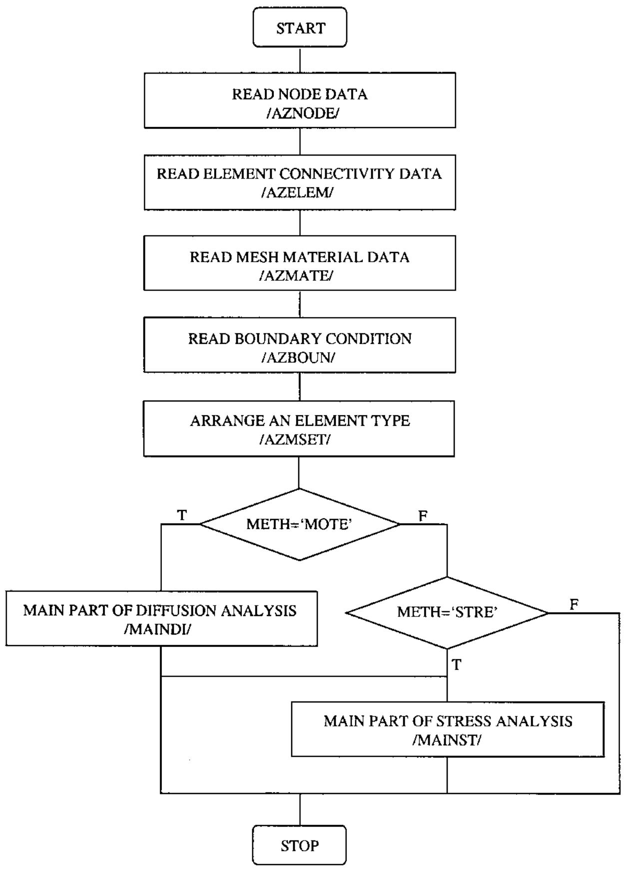

Fig. 11. Flow chart of the analyzer.

analysis. In the deformation-stress analysis, MAINST, the moisture-thermal stress due to the temperature and moisture gradients as well as the deformation are calculated. Figure 11 illustrates a main flow chart of the analyzer. The detail explanations of the subprogram of the analyzer are given below.

AZNODE: receives finite-element node data.

AZLEEM: receives finite element data.

AZBOUN: receives various boundary conditions: boundary conditions specified as a function of time and position, effect of latent heat during the phase change, and boundary conditions for stress and deformation analysis.

AZMSET: decides element type, namely triangular element or quadrilateral element. MAINDI: analyzes heat and moisture transfer.

MAINST: analyzes stress and deformation.

Temperature-Moisture Field Theory

For the analysis of heat and moisture transfer the following Luikovs coupled diffusion equations are considered:

$$C\frac{\partial T}{\partial t}=\nabla\cdot(K^M\cdot\nabla W+K^T\cdot\nabla T)+\dot{I}_q \tag{1}$$

$$\frac{\partial W}{\partial t}=\nabla\cdot(A^M\cdot\nabla W+A^T\cdot\nabla T+A^g\cdot Wg) \tag{2}$$

where T is the temperature, W is the moisture, C is the bulk specific heat per unit volume, $\dot{I}_q$ is the heat source function, K^M is the diffusion-thermal coefficient tensor, K^T is the heat conductivity tensor, A^M is the moisture diffusivity tensor, A^T is the thermal diffusion coefficient tensor, and A^g is the forced flux coefficient tensor. In Fig. 12, the schematic diagram of heat and moisture transfer problem is seen. During the drying process of a ceramic product, the flux and source of heat and moisture as well as traction are respectively subjected to the ceramic body dried and wetted zones simultaneously exist. The problem definition provides the boundary conditions expressed as follows:

$$T=T_a \text{ on } S_1 \tag{3}$$

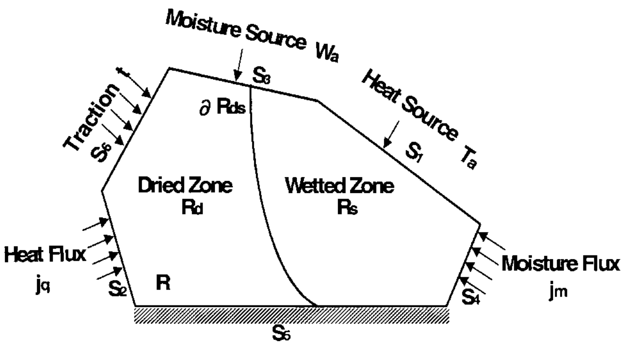

Fig. 12. Schematic diagram of the heat and moisture transfer problem.

$$k_q\nabla T\boldsymbol{n}+\boldsymbol{j_q}+\alpha_q(T-T_a)+(1-\varepsilon)\alpha_m\lambda(W-W_a)=0 \text{ on } S_2 \tag{4}$$

$$W=W_a \text{ on } S_3 \tag{5}$$

$$k_m\nabla W\boldsymbol{n}+\boldsymbol{j_m}+k_m\delta\nabla T\boldsymbol{n}+\alpha_m(W-W_a)=0 \text{ on } S_4 \tag{6}$$

$$S_1\cup S_2=\partial R \tag{7}$$

$$S_3\cup S_4=\partial R \tag{8}$$

where T_a is a prescribed temperature on the boundary S_1, j_q is the heat flux on the boundary S_2, W_a is a prescribed moisture on the boundary S_3, j_m is the moisture flux on the boundary S_4, k_q is a thermal conductivity, k_m is the moisture conductivity, n is an outward normal vector on the surface of the boundary, α_q is a convective heat transfer coefficient, α_m is a convective moisture transfer coefficient, ε is a ratio of the vapour diffusion coefficient to the total diffusion coefficient of the moisture, η is a heat of phase change, δ is a thermo-gradient coefficient, and δR is a boundary of the control volume R. Eq. (3) and Eq. (5) represent boundary conditions on the portion of the material boundary where constant temperature and constant moisture are prescribed, respectively. Eq. (4) and Eq. (6) also represent those on the boundary subjected to heat and moisture flux. Eq. (4) and Eq. (6) can be rewritten in the compact form as follows:

$$k_q\nabla T\boldsymbol{n}+\boldsymbol{j_q^*}=0 \text{ on } S_2 \tag{9}$$

$$k_m\nabla W\boldsymbol{n}+\boldsymbol{j_m^*}=0 \text{ on } S_4 \tag{10}$$

where

$$\boldsymbol{j_q^*}=\boldsymbol{A_q}(T-T_a)+\boldsymbol{A}_\varepsilon(W-W_a)+\boldsymbol{j_q} \tag{11}$$

$$\boldsymbol{j_m^*}=\boldsymbol{A}_\delta(T-T_a)+\boldsymbol{A_m}(W-W_a)+\boldsymbol{j_m}-\frac{k_m\delta}{k_q}\boldsymbol{j_q} \tag{12}$$

$$\boldsymbol{A_q}=\alpha_q \tag{13}$$

$$\boldsymbol{A}_\varepsilon=(1-\varepsilon)\alpha_m\lambda \tag{14}$$

$$\boldsymbol{A}_\delta=-\frac{k_m\delta\alpha_q}{k_q} \tag{15}$$

$$\boldsymbol{A_m}=\alpha_m-\frac{(1-\varepsilon)\alpha_m k_m\lambda\delta}{k_q} \tag{16}$$

Stress Field Theory

The governing equation in the stress field derived from a force balance at equilibrium can be expressed as follows:

$$\nabla\cdot\sigma+\boldsymbol{f}=0 \tag{17}$$

where σ is a stress tensor and **f** is a body force vector. Also, the boundary conditions can be described as follows:

$$\mathbf{u}=\mathbf{u_a} \text{ on } S_5 \tag{18}$$

$$\sigma\cdot\boldsymbol{n}=\boldsymbol{t} \text{ on } S_6 \tag{19}$$

where $\mathbf{u}_a$ is a prescribed displacement on the boundary S_5 and $\mathbf{t}$ is a traction on the boundary S_6, as seen in Fig. 12.

The basic assumption in a constitutive model in a stress field is that a strain tensor represents the sum of the strains caused by traction, temperature, and moisture:

$$\boldsymbol{e}=\frac{1}{E}(\sigma-\sigma_0)+\alpha\Delta T+\beta\Delta W \tag{20}$$

where $\boldsymbol{e}$ is a total strain tensor, σ is a stress tensor, σ_0 is an initial stress tensor, E is an elastic coefficient, α is a thermal expansion coefficient, ΔT is a temperature gradient, β is a moisture expansion coefficient, and ΔW is a moisture gradient. In the finite element formulation of a hygro-thermal stress problem, the thermal and moisture effects may be treated like that of an initial stress. The constitutive equation based on Eq. (20) can be defined as follows:

$$\sigma=E\cdot(\boldsymbol{e}-\alpha\Delta T-\beta\Delta W)+\sigma_0=E\cdot\boldsymbol{e}+\sigma'_0 \tag{21}$$

Following the standard finite element procedure, we can finally have

$$\sum_{e=1}^{E}([K]\{u\}-\{F\})_e=0 \tag{22}$$

where [K] is an element stiffness matrix defined as follows:

$$[K]=\int_R [B_u]^* \boldsymbol{E}[B_u]dR \tag{23}$$

and {f} is an element force vector expressed like follows:

$$\{F\}=\int_{\partial\Omega}[N_u]\boldsymbol{t}dR+\int_R[N_u]\boldsymbol{t}dR-\int_R[B_u]^*\sigma'_0 dR \tag{24}$$

Analysis Data

As the drying time goes by, the distributions of temperature, moisture content, principle stress, and strain are computed by the analyzer using the boundary conditions, initial temperature and moisture conditions, elements, nodes, material properties, analysis time, etc. provided by the pre-processor. Figure 13 and Fig. 14 show analysis results for temperature and moisture distributions at each node after 1 and 5 drying hours, respectively.

Fig. 13. Nodal temperatures at specified drying times.

Fig. 14. Nodal moistures at specified drying times.

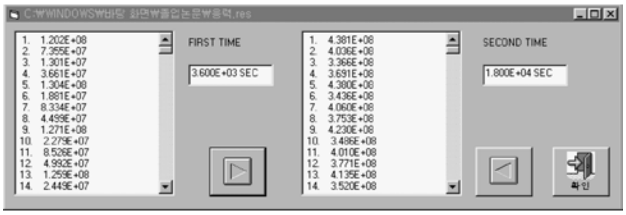

Fig. 15. Principal stresses in elements at specified drying times.

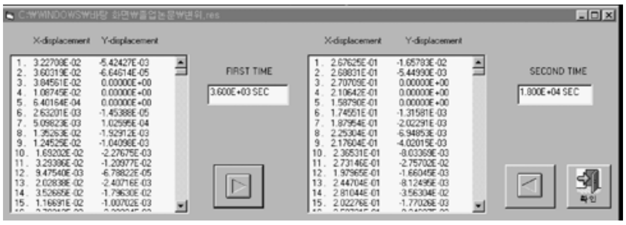

Fig. 16. Nodal displacements at specified drying times.

Figure 15 is an analysis result for the principle stress distribution and Fig. 16 shows the strain distributions in the x and y directions.

Post-Processor

Overview

The post-processor showing graphically or visually analysis results lets the designer examine the propriety of the design of the ceramic component. The post-processor consists of two parts: a post-processor interface module and the post-processor. The post-processor interface module conserves analysis results to transform to the input form of the post-processor. The post-processor, HY-VIEW, rapidly visualizes analysis results.

Post-Processor Interface Module

The post-processor interface module has 4 menus: file menu, output data menu, convert menu, and help menu. The file menu has functions of open and close of analysis result file, as seen in Fig. 17. The output data

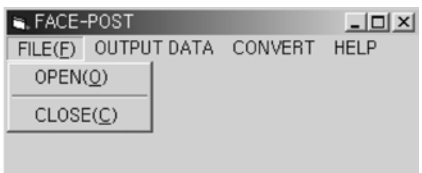

Fig. 17. File sub-menu in post-processor interface module.

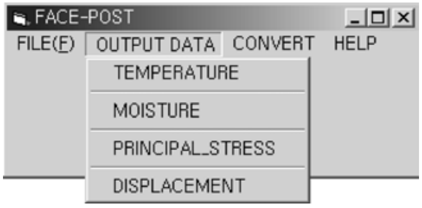

Fig. 18. Output data sub-menu in post-processor interface module.

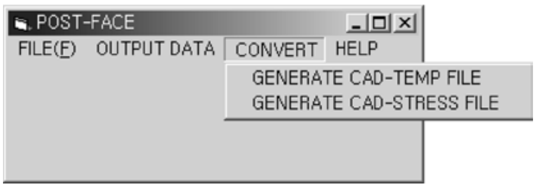

Fig. 19. Convert sub-menu in post-processor interface module.

menu has 4 sub-menus: temperature, moisture content, principle stress, and displacement. (see Fig. 18) The temperature sub-menu has a function showing temperature distributions at specified analysis times. The moisture sub-menu has a function showing moisture distributions. The principal stress sub-menu shows stress distributions at specified analysis times. The displacement sub-menu enlarges the displacement at each node. The convert menu makes a new data file needed in the post-processor from analysis results. This menu is shown in Fig. 19. Finally, the help menu is prepared to show the position of this program and giving the meaning of the words used in the post-

Fig. 20. Main menu in HY-VIEW.

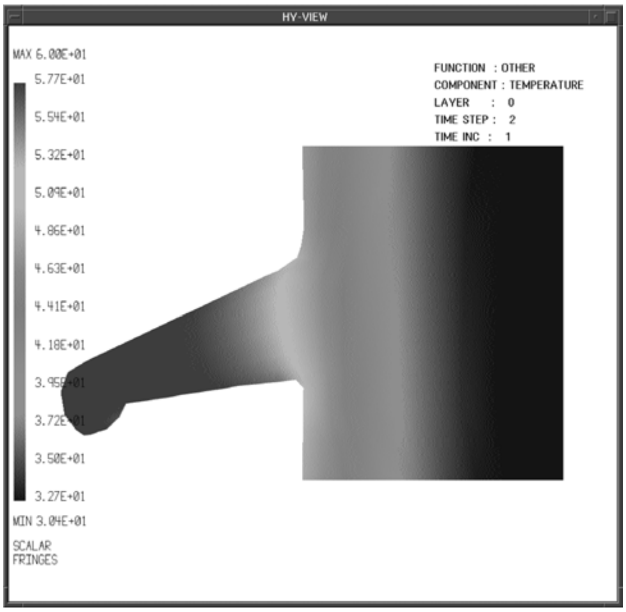

Fig. 21. Example of post-processing: temperature distribution.

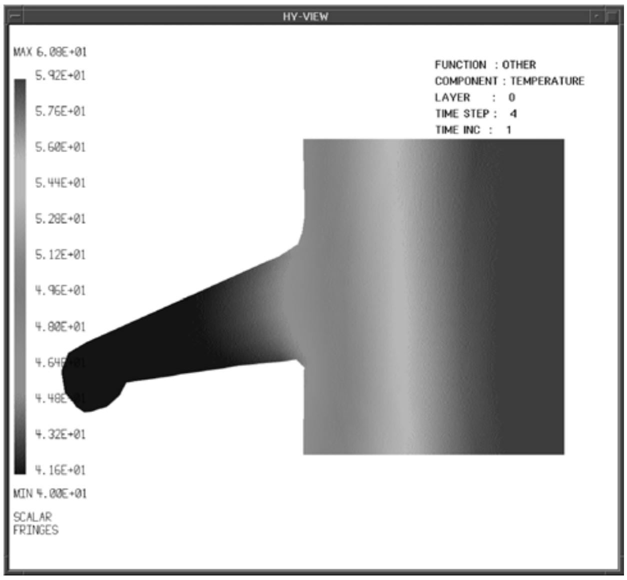

Fig. 22. Example of post-processing: moisture distribution.

processor interface module.

HY-VIEW

HY-VIEW, which is the main post-processor and works in the workstation computer, visually shows analysis results like temperature, moisture content, stress, deformed shape, etc. The strongest point of HY-VIEW is in the GUI, which has the function to add and delete a menu easily. HY-VIEW divides the screen into 3 sections: menu section in the upper left corner of the screen, graphics display section in the center or majority of the screen, and text window section in the bottom portion of the screen showing input and output text.

Figure 20 shows the 6 main menus of HY-VIEW, which are explained below:

① GLOBAL-COMMANDS: Here the principal role

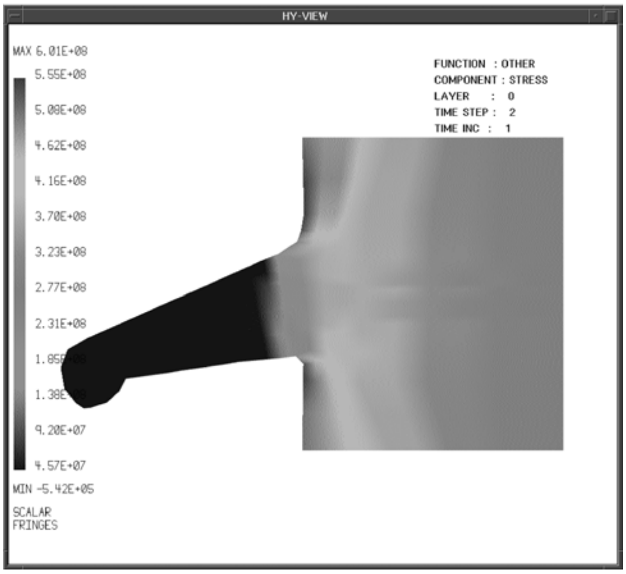

Fig. 23. Example of post-processing: stress distribution.

is to control the coordinates in the display, screen indication, name and color of product, and background color. Also, it is possible to rotate and move the object.

② DEFINE-GEOMETRY: Here basic geometric elements like node, line, surface, etc. are defined.

③ GENERATION-MESH: Here the coordinates of finite-element nodes are generated from the geometric model created connecting the geometric elements.

④ OPTIMIZE-MESH: Allows renumbering the mesh for the optimization of the simulation.

⑤ PREPARE-ANALYSIS: Here geometry, load, and material property in finite-element model can be added, changed, or deleted.

⑥ POST-RESULTS: Here analysis results are visualized on the screen and 3-dimensional visualization of the symmetric shape, coordinate transformation, expansion, reduction, etc. are possible.

Figure 21, 22, and 23 show the examples of HY-VIEW post-processor: temperature distribution, moisture distribution, and heat-thermal stress distributed inside the green ceramic during the drying process.

Conclusions

A finite element simulation system for ceramic drying processes has been developed. The conclusions derived in this study are as follows:

(1) Using the simulation system of ceramic drying processes, the drying characteristics of the green ceramic can be evaluated quantitatively.

(2) Using the simulation system, the analysis of the drying processes can be performed effectively and rapidly.

(3) GUI increases users convenience in developing the pre- and post-processor.

(4) The programming skills obtained from the development of the drying simulation system can be applied to those of other ceramic process simulation systems.

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