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EXPERIMENTS ON NATURAL CIRCULATION DURING PWR SEVERE ACCIDENTS AND THEIR ANALYSIS

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Abstract

Buoyancy-induced natural circulation flows will occur during the early-part of PWR high pressure accident scenarios. These flows affect several key parameters; in particular, the course of such accidents will most probably change due to local failures occurring in the primary coolant system (PCS) before substantial core degradation. Natural circulation flow patterns were measured in a one-seventh scale PWR PCS facility at Westinghouse R&D Laboratories. The measured flow and temperature distributions are reported in this paper. The experiments were analyzed with the COMMIX code and good agreement was obtained between data and calculations.

I. Introduction

It has been established for sometime (1,2) that natural circulation flows will occur in the PWR vessel and primary system during the course of the postulated high pressure accidents. The effects of these flows are far- reaching on the consequences of such accidents, e.g., they strongly affect, (1) the magnitude and rate of hydrogen generation, (2) time before core melting, (3) system temperatures, (4) fission product retention within PCS (5) fission product revaporization, and most importantly, (6) the potential for PCS piping failure before vessel lower head failure from core-melt attack. Some analyses to estimate the magnitude of these effects have been performed (3-7) and more are in progress. Validation of the methods employed in the severe accident analysis codes depends on the set of data obtained in an EPRI sponsored program of experiments on natural circulation flows, conducted at Westinghouse R&D laboratories, and their analysis at Argonne National Laboratories. The experiments conducted and analyses performed are described here.

II. Objectives

The general objective of the experimental part of this program is to provide pertinent data on flow patterns and velocity and temperature distributions for natural circulation flows in a PWR PCS during the postulated high pressure accidents. The general objective of the analysis activities in this program is to rationalize the data obtained and to extend the scope and applicability of the experimental information.

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The specific objectives of the experimental work were: (1) Determine the natural recirculation flow patterns, temperature and velocity distributions in the core and upper plenum regions. (2) Determine the natural circulation exchange between the upper head and upper plenum regions, as the upper plenum becomes heated. (3) Determine the effect of steaming flow on the recirculating flow in the core and upper plenum. (4) Determine the effect of heat removal through simulated steam generators on the temperatures and velocities of the recirculation flow patterns. (5) Observe the dynamics of hot leg flows, mixing in the steam generator inlet plenum and tube bundle flows. (6) Observe the effects on natural circulation of rapid venting of fluid from simulated pressurizer safety valves. (7) Simulate hydrogen generation in the core and determine if natural circulation is stopped by conversion of part of the fluid to lighter gas. (8) Simulate core blockage due to a fuel debris bed and observe the effects on natural circulation flows in the remaining intact core.

The first five objectives are concerned with the information on recirculation flow patterns in the reactor vessel, hot legs and the steam generators, while the last three objectives are concerned with the disruption of natural circulation flows due to events that may occur during an accident scenario e.g., safety valve operation, hydrogen generation and core blockage formation.

The specific objectives for the analysis work were: (a) analyze each experiment and determine the extent of agreement between measurements and calculations (b) determine the magnitude of multi-dimensional effects (c) perform scaling studies (d) perform pre-test analyses

III. Experimental Approach

A one-seventh scale model of a Westinghouse four-loop reactor system, shown in Figure 1, was used to perform the experiments. The model is comprised of a one-half section of the reactor vessel (sliced through a vertical, nearly-diametral plane), hot legs and two steam generators. The slice plane is covered with a transparent window to permit flow visualization and use of a laser-doppler anemometer to measure velocities. The core is simulated with electrically heated rods placed in an "egg-crate" type structure, containing slots, that models the flow resistance of fuel assemblies. Water and sulfur hexafluoride (SF_6) were used as analog fluids. Water tests enabled visualization of flow patterns through injection of a dye. Complete thermal-hydraulic similarity between the model and the prototype, for high pressure severe accident conditions, can be achieved with moderately-pressurized SF_6 gas. However, in the initial phase of the program reported here, all tests were performed at one atmosphere pressure. To accomplish the objectives, a number of steady state tests with water and SF_6 gas, and a few transient tests with SF_6 gas, were performed. Fluid temperatures were measured at 132 locations in all tests. In several steady state water tests, recirculation flow patterns were observed visually. Heat deposited by the recirculation flow in the cooler regions above the core was also measured. Based on the measured temperatures and rates of heat deposition in the cooler regions, recirculation flow rates and velocities were calculated. In some water and SF_6 tests, flow velocities were also measured directly at several locations using a laser-Doppler anemometer. By using the data from these atmospheric pressure tests and scaling laws, flow patterns, velocities and temperatures expected in the future high pressure tests have been predicted.

A forty-nine tube model acrylic (transparent) steam generator, shown in Figure 2, was constructed and substituted for one of the simulation steam generators. It provided visual evidence of the natural circulation in some tubes from the inlet to outlet plenas and return flow in the remainder of the tubes. Flow initiation from an unstable equilibrium was observed. The fluid dynamics of stratified hot leg flow, mixing in the inlet plenum and tube bundle flow were correlated using simple models and the experimental results.

Large flows toward the pressurizer surge line in one of the hot leg resulting from the rapid venting through simulated safety valves can overwhelm natural circulation in steam generators, hot legs, and to some degree in the upper plenum and core. The transient effects and resumption of natural circulation were studied using SF_6 gas venting to a vacuum system. The fluid mass vented was about 8% of the fluid in the system. Two types of experiments were conducted; single vent cycles followed by a long time for the system to return to equilibrium, and regularly repeated, periodic vent cycles with a short time between vent cycles. Two venting flow rates were used for each.

The effects of hydrogen generation in the core were observed by rapidly withdrawing SF_6 from the central region and simultaneously replacing it with helium. Following the exchange of about 40% of the gas, in this manner, helium concentrations were measured at later times and the effects on natural circulation were inferred from temperature measurements.

Core blockage effects were simulated by blocking a number of fuel assemblies in the central core region with graded beds of spheres which greatly increased flow resistance. Flow of water was observed using the dye tracer method and effects on fluid temperature in the core region were measured.

Section V briefly describes the flow similitude achieved between the model and prototype. Some representative experimental results are provided in Section VI.

Analysis Approach

It was recognized quite early in this program that the natural circulation flows will have a multi-dimensional character in the core region and possibly in the hot legs and steam generators. Mixing of hot and cold flows and of light and heavy fluids will occur in certain regions of the PCS and that may have an important bearing on the strength of the natural circulation flow fields. These physical features led to the choice of COMMIX 1-A code (8) for analysis of the experiments. This code developed at Argonne National Laboratories has been used extensively in analysis of single phase flows in complex multi-dimensional geometries (rod bundles, plena, steam generators, piping, etc.). It also

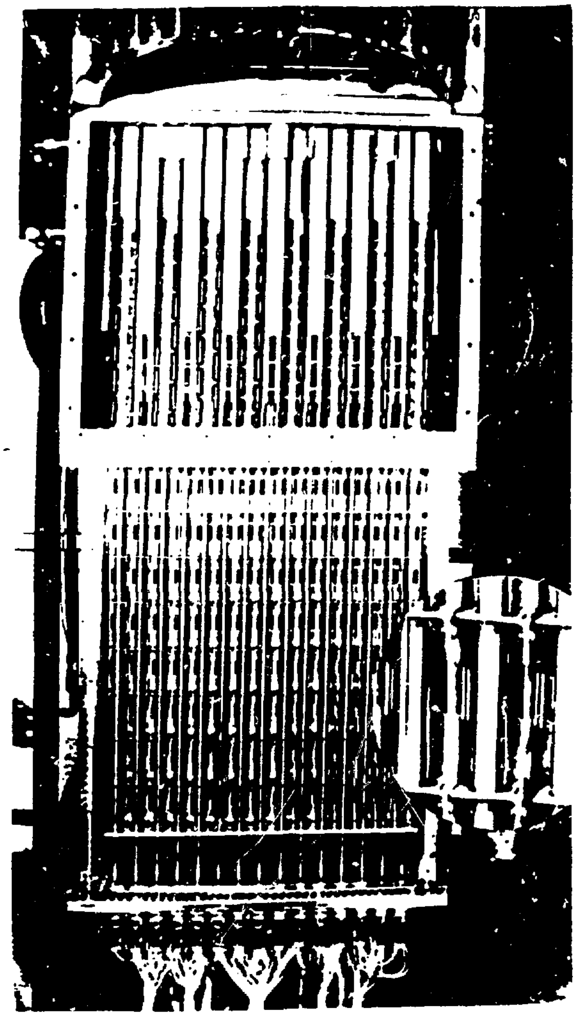

FIG.1 One-Seventh Scale Model

FIG.2 Model Steam Generator

FIG.3 Stratified Hot Leg Flow

incorporates mixing models for various flow fields. The code has been validated for many fast reactor steady-state and transient applications, and has recently been applied to water reactor design and safety analyses.

Section VII describes the COMMIX numerical model and section VIII provides representative results from analysis of the atmospheric pressure water and SF_6 tests. Finally Section IX provides conclusions for both the experimental and analysis parts of this study.

V. Flow Similitude Between Scale Model and Prototype

In a previous paper (9), the parameter controlling similitude for the natural circulation flow fields in the particular configuration of a TMLB' accident was derived. It was found that good flow similitude between the scale model and the prototype can be achieved by having similar values for the parameter ($g \rho^2 \beta q L^2/C_p \mu^3$), where ρ β, C_p and μ, are respectively, the density, coefficient of density change with temperature, heat capacity, and viscosity of the fluid; q is the heat flux and L is the length scale. The 1/7th scale model having a reduction of this parameter by a factor of 49 needs to use a fluid with higher values of ρ and β and lower values of C_p and μ than steam or steam-hydrogen mixtures. Fortunately sulphur hexafluoride (SF_6); a gas used extensively as a dielectric medium, stable at high temperatures and non condensible at temperatures higher than 316K, has very favorable properties. Table I compares the values of the similitude parameter and the Reynolds number for the one-seventh scale model and the prototype. It is seen that water and SF_6 at low pressure can not match the required values of the parameters; however, SF_6 at 400 to 600 psia provides parameter values in the range of interest. The next phase of the natural circulation experimental program will use SF_6 at high pressure in a new facility constructed for this purpose.

VI. Some Representative Results

A summary of the water and SF_6 steady-state natural circulation tests performed at one atmosphere is given in Table II. Water circulation flows were observed visually in the vessel and the hot legs. The hot flow ascended in the middle and cold flow descended at the core periphery and moved across the heater rods to the middle of the core. The upper plenum was found to be quite well mixed. The upper plenum hot fluid was found to flow to the steam generators in the upper half of the hot legs. The lower half of the hot legs was occupied by the cold fluid returning from the simulated steam generators. This is shown in Figure 3 where a characteristic inclined separation plane is observed. This configuration was found (9,10) to maximize the flow to the steam generators.

The measured temperature distribution in one of the water tests is shown in Figure 4. The measured temperatures conform to the visual flow observations. The corresponding velocities measured with LDA are shown in Figure 5. Very similar results are obtained in the SF_6 steady-state experiments.

The 49 tube acrylic steam generator was connected to one of the hot legs and the flow patterns observed by adding a dye. A most interesting

Table I

Natural Circulation Similitude Parameter for a PWR and for a 1/7 Scale Model with Various Fluids

Fluid	Steam	Steam+ 20% H_2	Steam+ 50% H_2	Water	SF_6 gas	SF_6 gas	SF_6 gas
Pressure (psia)	2400	2400	2400	14.7	14.7	400	600
L (ft)	1	1	1	1/7	1/7	1/7	1/7
$(g\rho^2\beta qL^2/C_p\mu^3)\times10^{15}$	38.1	23.3	2.31	0.0008	0.0009	9.99	23.6
V (ft/sec)	1.27	1.28	1.29	0.126	0.875	0.760	0.723
$Re\times10^{-4}$	9.51	6.10	2.85	0.292	0.309	6.8	9.07
T (K)	1088	1255	1588	330	366	444	411
T_h(K)	1183	1374	1750	336	412	484	435
T_c(K)	993	1136	1427	324	320	404	387

Table II

Summary of Steady-State Experiments With Fluid At One Atmosphere In Scale Model with Simulated Steam Generators

Test Number	Fluid	Power Level	Natural Circulation To Upper Head	"Steaming" Simulated By Upward Flow From Lower Plenum	Cooling Rate By Simulated Steam Generators Left	Right
1	Water	Full	No	No	None	None
2	"	"	"	High	"	"
3	"	"	Yes	No	"	"
4	"	"	"	High	"	"
5	"	"	"	No	High	High
6	"	"	"	"	Low	Low
7	"	"	No	"	Med.	None
8	"	"	"	"	None	Med.
9	"	"	Yes	Low	Low	Low
10	"	"	"	High	Low	Low
11	SF_6	Full	Yes	No	None	None
12	"	"	"	High	None	None
13	"	"	"	No	High	High
14	"	"	"	"	Med.	Med.
15	"	"	"	"	Low	Low
16	"	"	"	Low	"	"
17	"	Half		No	Med.	Med.
18					Low	Low
19	"				None	None

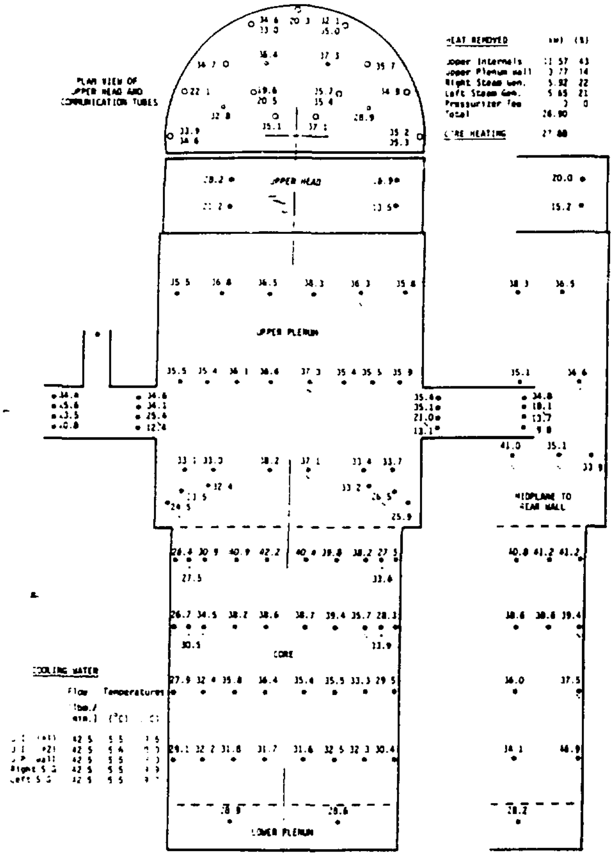

FIG.4 MEASURED TEMPERATURES
TEST 5

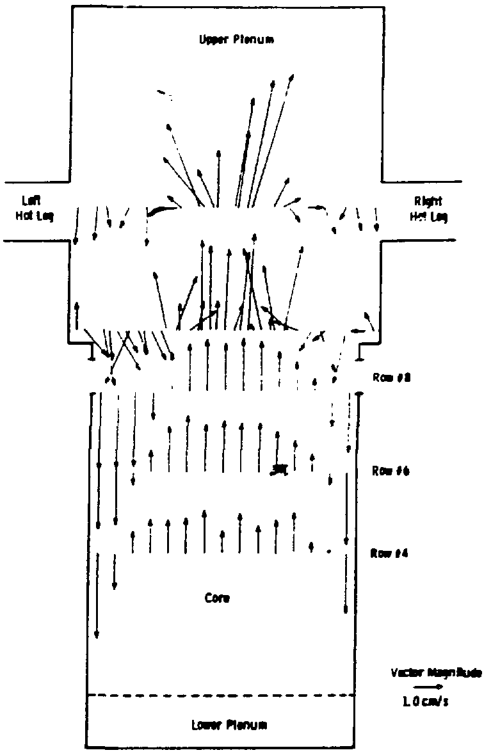

FIG.5 MEASURED VELOCITIES
TEST 5

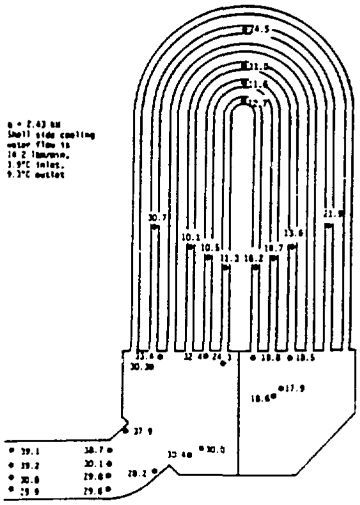

FIG.6 MEASURED TEMPERATURES
IN MODEL STEAM GENERATOR

flow field was observed; namely, the hot flow entering the steam generator inlet plenum mixed with some of the cold fluid resident there, however, a thermal front was established in the tubes and some of the tubes (approximately one-third) carried the buoyant fluid to the cold plenum of the steam generator. Continuity considerations prompted cold plenum fluid to return to the hot plenum as a cold stream through the rest (approximately two-third) of the tubes. Thus, the steam generator mass participated in the heat exchange process that the hot fluid from the core undergoes with the the PCS. The measured temperature distributions in the steam generator plena and tubes are shown in Figure 6. Tests with the 49 tube steam generator were also performed with SF_6 as the simulant fluid.

The safety relief valve venting tests were performed with the 49 tube steam generator connected to the right hot leg in which the SF_6 venting took place. Changes in the themocouple temperatures were observed. In the case of single vent tests (8% of SF_6 withdrawn rapidly; then vent closed), hot upflow, instead of cold down flow, resulted in the core periphery next to the right hot leg for the duration of the vent flow. The original flow patterns were reestablished soon after the vent was closed. The vessel temperatures showed very little change in regions away from the hot leg.

In the case of periodic venting, the steam generators transferred 50 to 75% more heat, since they were receiving a forced alternating flow through the tube bundle and the plena.

In the tests with He addition and SF_6 withdrawal, heated (to same temperature as SF_6 at injection location), a large amount of He was introduced in approximately 40 seconds. The He concentration in the upper plenum was measured as a function of time. A temporary stratification was found to occur and the hot leg flow was disturbed. It was found, however, that He mixed reasonably fast and the natural circulation flow fields were reestablished.

Three tests were conducted with blockages of various porosities to restrict axial flow in 41 out of 104 fuel bundles. Measured temperature distributions showed that the effect of blockages was quite local; the buoyant flow fields , a little distance from the blockage, were not affected significantly.

VII. COMMIX Numerical Model

Figure 7 shows the axial and horizontal partitioning of the three dimensional model of the atmospheric pressure facility with simulated (drum) steam generators. The cartesian geometry used 8 x 31 horizontal and 14 axial partitions i.e., a total of 1300 computational cells. The internal structure geometric obstructions to fluid flow were represented by appropriate volume and directional-surface porosities. Thermal inertia for internal solids was represented through 24 thermal structures, and heat transfer and friction coefficients were calculated through 6 heat transfer correlations and 13 force structures. The secondary side of the drum steam generators were modeled by two separate open systems of 48 computational cells having inlet and outlet for the secondary fluid.

VIII. Some Representative Analytical Results & Comparisons with Data

All of the tests shown in Table I were analyzed with the COMMIX numerical model shown above. The calculated velocity and temperature distributions for one of the water tests are shown in Figure 8. They compare quite well with the data shown in Figures 4 and 5. The calculated values for heat removed in KW were as follows: upper internals = 11.54; upper plenum wall = 3.86; left steam generator = 5.98, right steam generator = 5.98. An excellent agreement is indicated when compared to the measured heat balance shown in Figure 5 for this test. Similar good agreement of heat balances were obtained for the SF_6 tests. Detailed comparisons of the calculated and measured temperatures were made; there were differences; nevertheless, the COMMIX calculations provided reasonably good representations of the flow and temperatures assymetries found in the experiments.

Calculations were also performed for the experiments in which safety relief valve venting was simulated. It was found that the natural circulation velocity fields were reestablished approximately 15 seconds after the venting stopped. Higher temperatures and greater steam generator heat removal were calculated for the loop with the vent, as also observed in the experiments.

A COMMIX calculation was also performed with the blockage represented as in the experiment. Reasonably good agreement was obtained with the measured temperature data.

IX. Conclusions

The following set of conclusions were derived from the experiments conducted with water and SF_6 at atmospheric pressure and their analysis with the COMMIX Code. Complete flow similitude will be obtained in the high pressure SF_6 tests and the validity of these conclusion will be verified. (1) Recirculation flow obeys the following relationship: $Rey^2 = CGr$, where Rey and Gr are respectively, the Reynolds and Grashof numbers. (2) Recirculating flow patterns are nearly symmetric, except near the hot legs and in the upper head. (3) Upflow from the bottom of the reactor vessel causes the recirculation zone in the core to move to a higher elevation. (4) Fluid in the upper plenum was well mixed. (5) Flow in the hot legs is well stratified, and there is very little mixing between the top hot stream and the bottom cold stream. (6) Hot leg flow maximizes itself and can be simply, but approximately, predicted. (7) Recirculating single phase flow rapidly develops in steam generator tube bundles and transfers heat to the metal tubes. (8) Mixing occurs in the steam generator inlet plenum. The one-seventh scale model with SF_6 has a mixing parameter near 0.7. (9) Fewer than half the steam generator's tubes may carry fluid from the inlet plenum to the outlet plenum, but the reduction in heat transferred is small. (10) Natural circulation flow restores itself readily to original condition after vent is closed. (11) Heat transfer in S.G.'s increases 50% to 75% with periodic venting. (12) Core flow patterns are affected very little, except for the boundary under hot leg with pressurizer surge line. (13) COMMIX numerical model represents the experiment detail quite well. (14) The COMMIX results are in good agreement with measured velocity and temperature distributions.

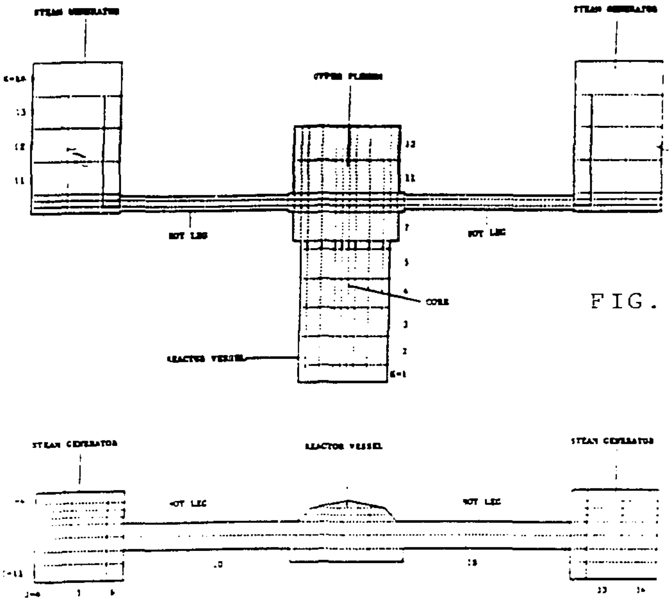

FIG. 7 COMMIX NUMERICAL MODEL

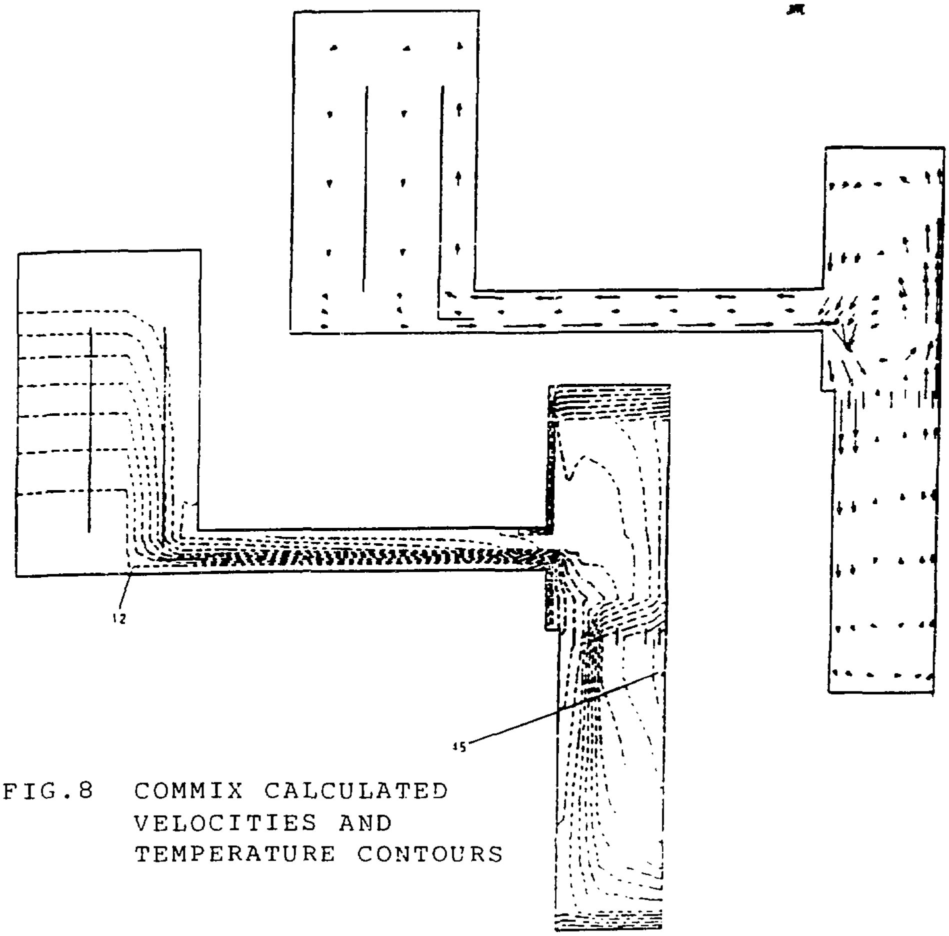

FIG.8 COMMIX CALCULATED VELOCITIES AND TEMPERATURE CONTOURS

(15) COMMIX was able to analyze the valve venting transients and predicted the observed trends.

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