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Technical Progress Report No.1

DEVELOPMENT OF A VORTEXING COMBUSTOR (VC) FOR SPACE/WATER HEATING APPLICATIONS (COLD FLOW MODELING)

To

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MASTER

SUMMARY

The Catholic University of America (CUA) started a 27-month experimental/analytical study on the cold flow modeling of coal-firing Vortexing Combustion (VC) technique for commercial heating applications having a firing rate of 2 - 4 MMBtu/hr. This technical progress report No.1 summarizes the work performed at CUA during the period of April 7, 1987 to July 31, 1987.

Research efforts on the refinement of VC concept and system design, and mathematical modeling of VC processes were made. A thermal analysis of different VC arrangements concludes that sub-adiabatic combustion VC system featuring a high thermal efficiency and a low excess air factor is best suited for our purpose. The conceptual design, configuration, and performance of a 3 MMBtu/hr sub-adiabatic VC system are discussed in details. Formulations of the math models for both gas and particle flows in a VC unit are established by adopting Algebraic Stress Model (ASM) to account for the turbulence in the strong swirling flow in the VC. The current numerical work focuses on the finite difference formulation of gas/solid flows and the development of the associated computational code.

The research of this contract has been progressing on schedule. No major changes on the project or staff are expected. Future works include design and testing of a small cold VC test facility, development of the vortex generator, and numerical solution of gas/particle flow fields.

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SECTION 1

REFINEMENT OF VC CONCEPT

Coal, the largest energy reserve in the world, has regained its attraction due to the low price since the 1973 oil embargo. The number of coal-fired installations and associated researches have been constantly increasing since then. The existing coal-combustion technologies, namely, stoker-fired combustion, pulverized coal-fired combustion, and fluidized-bed combustion, must be reevaluated and modified to meet the ever stringent environmental and economic needs. A recent review of these conventional coal-firing techniques has shown that each of these techniques has its own inherent problems and an innovative coal-firing method is highly desirable [1].

The Vortexing Combustion (VC) technique proposed in this study integrates the advantages of cyclone combustor, multistage combustion, fluidized-bed combustor, and stoker-fired combustor while eliminates their disadvantages. It is potentially characterized with simple and compact combustor configuration and control, high carbon conversion and heat release rate due to large gas-solid slip velocities in the strong swirling flow, and low SOx, NOx, and particulates emission due to sulfur sorbent addition, staged combustion, and centrifugal ash collection. An evaluation of technical performances of different VC arrangements was made, and based on that a conceptual design of the best arrangement, sub-adiabatic VC system, was completed [1].

1.1 Evaluation of VC Thermal Systems

Analysis of the thermal performance of four VC arrangements: adiabatic, non-adiabatic, partially adiabatic, and sub-adiabatic, was made based on the overall heat and mass balances. The major results and system parameters are summarized in Table 1. The details of VC system configurations and the specific thermal analyses can be found in [1]. According to the calculations, the adiabatic or partially adiabatic VC systems, which employ little heat-removal surface and generates mainly hot flue gases, have low thermal efficiencies for both cases with or without air preheating. Higher thermal efficiencies can be achieved via either the non-adiabatic or sub-adiabatic VC arrangements. However, lower carbon conversion rate and poorer fuel ignition are likely to occur for non-adiabatic system due to the cooling effects (heat absorption) in the lower combustion chamber. This study also indicates that the sub-adiabatic VC system, which combines the merits of both adiabatic and non-adiabatic combustions, is the most promising design for an optimal VC system performance [1].

Fig. 1 shows the schematics of the sub-adiabatic VC system where the lower part of the combustion chamber is refractory-lined (adiabatic), and the upper chamber is lined with cooling surfaces (membrane wall, non-adiabatic). The adiabatic, refractory-lined wall at the lower chamber is maintained at a higher temperature, where fast ignition and stable initial combustion of coal particles or coal-water slurry droplets can be favorably completed. The cooling surfaces in the upper chamber absorbs the majority of heat released by coal combustion and produces the saturated steam. The total enthalpy of flue gases exiting the combustor and the heat loss in exhaust gas through stack are thus reduced. The major parameters and performance of sub-adiabatic VC system are similar to that of the non-adiabatic system, as shown in Table 1.

1.2 Working Principle and Configuration of the Sub-adiabatic Vortexing Combustor

A schematic diagram of the sub-adiabatic vortexing combustor is shown in Fig. 2 and the system shown in Fig. 1. The following considerations were carefully taken in the design process:

(a) Adopting the vortex generator design concept previously developed from our group to give a longer particle residence time for complete combustion

(b) Fully utilizing the large slip velocity and vigorous mixing between gas and solid phases to enhance the coal combustion, pollution control reactions, and heat transfer processes

(c) Maitaining fast ignition, stable and self-sustaining combustion by the design of a radiation cylinder (central exhaust pipe) and the adiabatic lower chamber wall

(d) Lowering the excess air factor and adjusting the secondary air injection to minimize the heat losses in exhaust gases and the NOx emission by staged control.

In Fig. 2, the upper header(1) is provided to collect the steam/water mixture generated in the membrane wall(2) which, absorbs heat in the combustion chamber and maintain the temperature of the exiting flue gases at close to 1652 °F. The lower header(3) feeds treated water to the membrane wall to form a natural circulation of the steam/water loop. The location of coal water mixture injection nozzles is denoted by (4). Primary air of about 35% of the total combustion air, is injected into the combustion chamber by a set of fuel nozzles(5) mounted on the lower combustion chamber. Additional air nozzles are also arranged at the same level as (5) for establishing a horizontal air curtain to prevent sedimentation of newly-fed coal particles.

L-valve(6) with small fluidizing air is used for the bottom ash drainage. A light-weighted thermal insulating layer(7) can be applied to the outside of the membrane wall in the upper chamber to minimize the wall conduction heat losses. Air and small amount of porous coal particles may be injected, as needed, at the upper chamber(8) for NOx emission and temperature control. The central radiation cylinder(9) directs the flue gases (exhaust pipe) and also provides the thermal inertia (as a radiative heating source) for rapid fuel ignition and stable combustion. The middle air nozzle assembly(10) provides high speed air jet to strengthen the needed vortex flows in the chamber, and supply oxygen for the burnout of coal particles. Limestone particles are also fed through the middle nozzles for sulfur retention. The gas burner(11) is used in the start-up operation. The walls of the lower chamber(12) are laid with firebricks and insulating material to form an adiabatic zone for improved ignition and combustion.

SECTION 2

MATHEMATICAL MODELING OF GAS-PARTICLE FLOWS AND COAL COMBUSTION IN VORTEXING COMBUSTORS

2.1 Main Goal and Previous Work

As a new coal-firing technique, the VC process presents a challenge in the developmental efforts, both in experimental and analytical works. To reliably ignite, stabilize, and intensify ultrafine coal and coal-water slurry flames in the vortexing combustor is crucial for a satisfactory operation and is challenging due to the compact combustor volume and the relatively low combustion temperature required for non-slagging ash removal. In designing such a combustor, it is desirable to simulate and optimize the key design parameters, such as, the inlet parameters (primary and secondary air flowrate, and coal feed rate), combustor configuration (nozzle diameter, position and angle, chamber height and diameter, exhaust pipe dimension, etc.), and the initial particle (or droplet) size and its distribution.

Mathematical (numerical) modeling of fluid/particle flow, heat transfer, and combustion processes in coal combustors has been extensively developed in the past two decades. As a method of computer-aided design, the modeling technique has been gradually recognized as a powerful tool in the design of coal combustors. Not only it can significantly reduce the efforts in experimental studies, but it can supplement the measurements to give insights of the controlling physical mechanisms and logical trends of a particular combustion process.

Modeling of cyclone-type of flows without combustion was reported by several researchers [2,3] and was recently reviewed in details in [4]. The use of standard $k - \varepsilon$ two-equation model has been very popular for isotropic turbulent flows. Although many corrections [5] were introduced to extrapolate to non-isotropic flows, such as strong swirling flows like ours, the calculated results were seldom close to the experimental findings. The recently-developed Algebraic Stress Model (ASM) accounting for non-isotropic turbulence [6] appears to be better suited for our VC gas flows than the standard two-equation model. In the open literatures, little was reported for strong swirling flows with combustion except the work of Boysan et al. [7], where the cyclone combustor was simulated by the ASM gas turbulence model and the stochastic trajectory particle model. Although, Boysan's results can give some plausible gross features of the flow field, the coal devolatilization and char combustion processes were oversimplified, which led to a poor agreement with measurements. For swirling reacting gas flows, the usefulness of different turbulence models have not yet been fully tested and assessed. For reacting particle flows, the approach by either trajectory model or the continuum model has also not been clear. The literature generally indicated that neither was satisfactory.

2.2 Intended Modeling Efforts

The present modeling work plans to use the ASM turbulence model for gas phase together with the continuum-trajectory model for reacting particle phase [8, 9]. The swirling gas-particle flows and heat transfer in VC processes are to be simulated simultaneously with moisture evaporation, coal devolatilization, and char combustion. For gas-phase reactions of volatile and CO, the Eddy-Break-Up-Arrhenius model will be used to account for the effect of turbulence and chemical kinetics on reaction rate of gas species. Three surface reactions, a two-equation devolatilization model, and a diffusion-kinetic char combustion model will be incorporated in modeling coal combustion. The LEAGAP algorithm will be used as an overall solution technique; and the SIMPLE algorithm will be used as the numerical technique for the gas phase. The details of the formulation of the axisymmetric swirling gas-particle flows with gas and particle combustion in cylindrical coordinates is given in the Appendix.

The math models for VC processes can be conceptually divided into four sub-models: (a) gas phase flow field (gas turbulence and reaction models), (b) particle phase flow field (continuum /trajectory model), (c) particle combustion (evaporation, devolatilization, and char combustion models), and (d) radiative heat transfer (heat flux model). The intended modeling work will include the following efforts:

(1) Establishing basic governing differential equations, specifying proper boundary conditions, and selecting associated models

(2) Selecting the efficient numerical procedures and available computer codes

(3) Modifying the original codes or developing the specific new codes to match with the resultant theoretical models

(4) Performing numerical predictions, making comparisons with experimental results, assessing the validity and limitation, and implementing the predicted results for optimal VC design.

2.3 Accomplishments

The formulation of the axisymmetric confined swirling gas flow in the VC system has been made. The derivations of the continuity, momentum, energy, and gas species equations, taking into account gas and particle combustions in the cylindrical coordinates are listed in Appendix. A computer code TEACH-T is selected as the basic code, on which our own code will be developed. Since TEACH-T code is primarily for non-swirling single-phase turbulent flows without combustion, a series of work to modify the code is currently conducted. The modification efforts include: establishing new grid meshes to fit the geometry of the VC; developing a new subroutine for calculating the swirling field (tangential velocities); and selecting proper boundary conditions. Preliminary predictions of the swirling gas flow field will be made soon.

SECTION 3

RESEARCH CONTINUATION

The progress of this project has been on schedule. A small (10" I.D.) cold VC test model system is being designed, fabricated, and assembled. Development, testing, and modification of the vortex generator will continue upon the completion of the small cold model system. The effects of air flow rate, nozzle location and orientation, and other operational parameters of the vortex generator on gas and particle flow fields will be explored. Instrumentation for the measurement and sampling of the gas-particle vortexing flow will be established.

A numerical calculation procedure for the VC math models will be developed. Efforts of implementing the TEACH-T code for gas flow calculations will continue. A series of numerical simulations on the single-phase vortexing flow field by using the ASM model will be performed, and the experience obtained will be incorporated in the development of a VC computer code involving two-phase flow, coal combustion, and heat transfer.

REFERENCES

[1] Hu, Z-G, "Conceptual Design of Vortexing Combustor (VC)", research report to Prof. S. Nieh, Dept. of Mechanical Engr., Catholic U. of America, Washington, DC, July 1987.

[2] Gupta, A.K., D.G. Lilley and N. Syred, Swirl Flows, Abacus Press, 1984.

[3] Boysan, F. and J. Swithenbank, "Numerical Prediction of Confined Vortex Flows", Numerical Methods in Laminar and Turbulent Flow, Pineridge Press, Swansea, UK, 1981.

[4] Sloan, D.G., P.J.Smith and L.D. Smoot,"Modeling of Swirl in Turbulent Flow System", Progress in Energy and Combustion Science, V. 12, pp. 163-250, 1986.

[5] Boysan, F. and J. Swithenbank, Rep. HIC 365, Dept. of Chem. Engr. and Fuel Tech., Sheffield U., 1981.

[6] Khalil, E.E., Joint ASME/AICHE 18th National Heat Transfer Conf., Paper No. 79-HT-31, 1979.

[7] Boysan, F. and J. Swithenbank, "A Fundamental Mathematical Modeling Approach to Cyclone Design", Trans. Inst. Chem. Engr., V. 60, pp. 222-230, 1982.

[8] Boysan, F. and J. Swithenbank, "Modeling Coal-fired Cyclone Combustors", Combustion and Flame, V. 63, pp. 73-85, 1986.

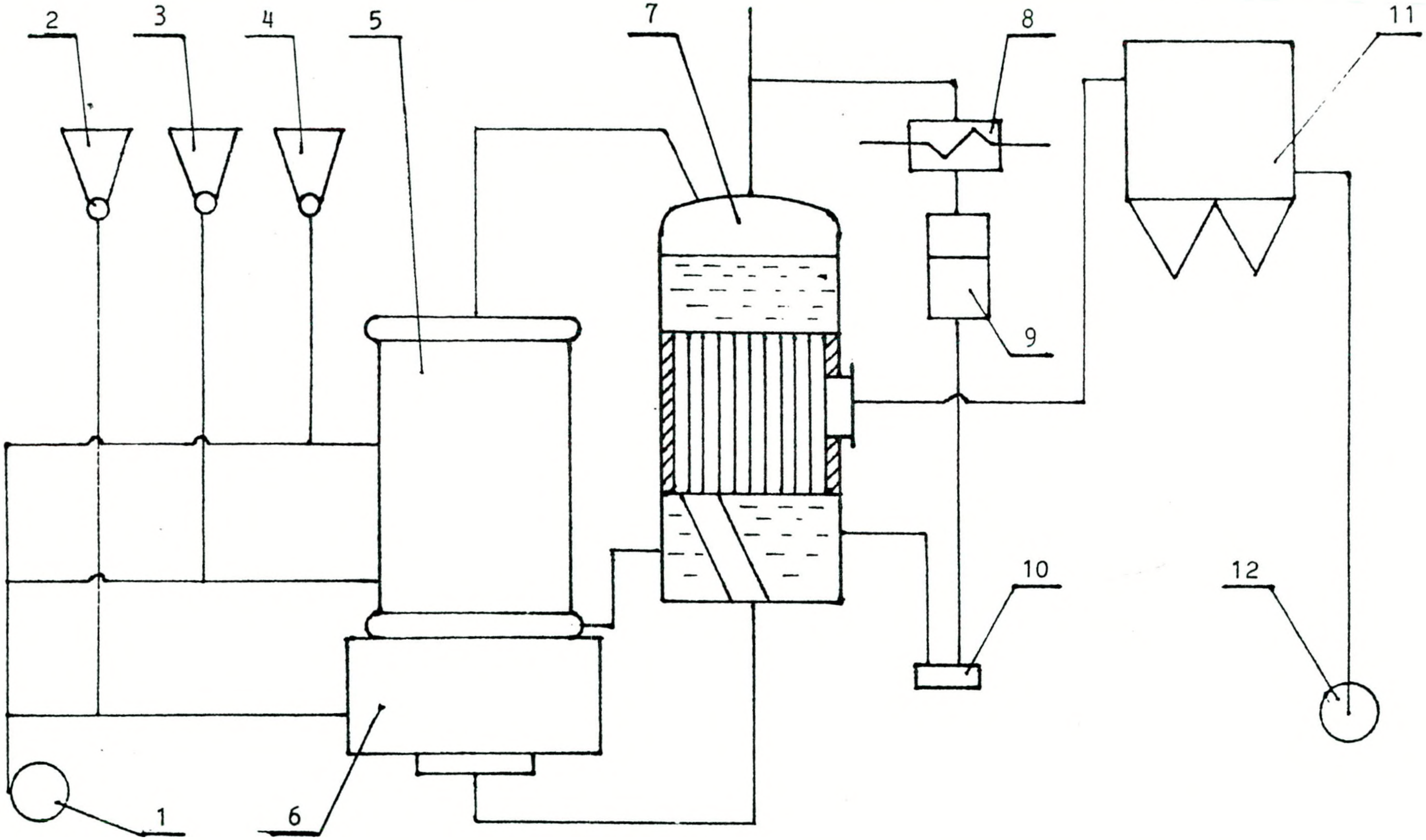
[9] Zhou, L-X, "Mathematical Modeling of Gas-Particle Flows and Coal Combustion in Vortexing Combustors", research report to Prof. S. Nieh, Dept. of Mechanical Engr., Catholic U. of America, Washington, DC, July 1987.

TABLE 1

Major Parameters of the VC Design for Different Thermal Systems

VC SYSTEM		ADIABATIC		NON-ADIABATIC (SUB-ADIABATIC)		PARTIALLY ADIABATIC
ITEM	Unit	A*	B**	A	B	B
Fuel (Coal) consumption	lb/hr	350	350	350	350	350
Air Flow rate	SCFM	1393	2017	619	646	1511
Exhaust gas						
temperature	°F	338	338	338	338	338
flow rate	SCFM	2502	3487	1269	1269	2766
Heat Loss in exhaust gas	%	15.7	21.5	8.48	8.48	19.0
Overall thermal efficiency	%	76.6	70.4	83.9	83.9	73.4
Excess air ratio						
at VC exit	-	2.64	3.75	1.20	1.20	2.81
at VC inlet	-	2.59	3.70	1.15	1.15	2.81
Gas temperature at VC exit	°F	1652	1652	1652	1652	1652
VC combustor						
I.D.	ft	3.28	3.28	3.28	3.28	3.28
Height	ft	6.42	6.42	6.42	6.42	6.42
Radiative heat surface	ft^2	-	-	66.2	71.8	66.2
Exhaust pipe (rad. cylinder)						
Height	ft	4.60	4.60	4.60	4.60	4.60
O.D.	ft	2.5 1.6	2.5 1.6	2.5 1.6	2.5 1.6	1.6
Gas velocity in						
VC chamber	ft/s	27 15	37 22	13 7	13 7	28
Exhaust pipe	ft/s	46 19	66 262	22 88	22 88	49

* A---Without air preheating, ** B---With air preheating



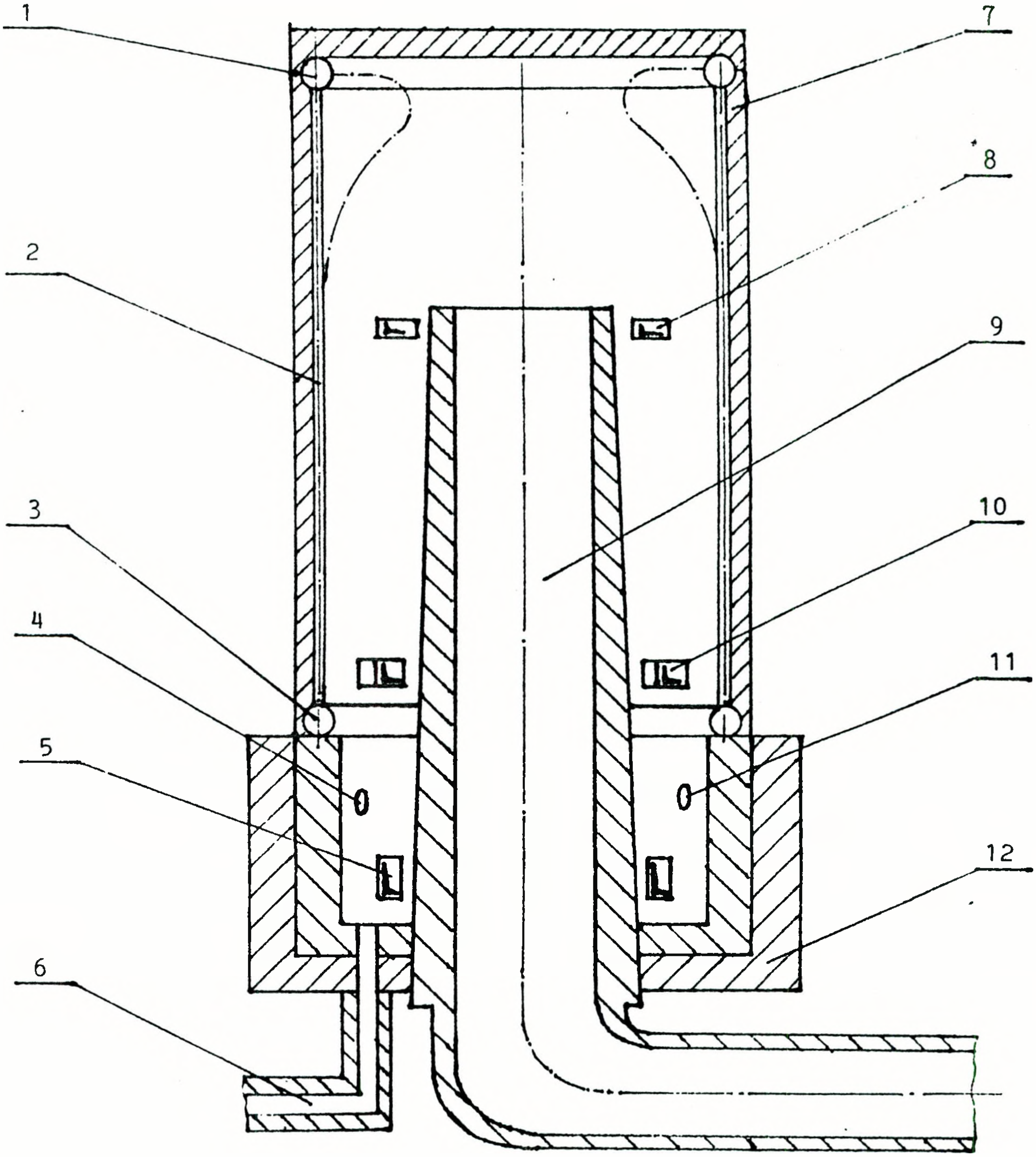
1 - F.D. Fan 2 - Coal bin 3 - Limestone bin 4 - Char bin

5 - Upper part of VC 6 - Lower part of VC 7 - Steam generator

8 - Heat exchanger 9 - Feed water 10 - Feed pump

11 - baghouse 12 - I.D. Fan

Fig. 1 The sub-adiabatic combustion VC thermal system



1 - Upper header
2 - Membrane wall
3 - Lower header
4 - CWM nozzles
5 - Lower nozzles
6 - L-valve
7 - Insulating layer
8 - Upper nozzles
9 - Radiation/exhaust pipe
10 - Middle nozzles
11 - Start-up burners
12 - Insulating wall

Fig. 2 Schematic diagram of the sub-adiabatic combustion vortexing combustor configuration

APPENDIX

MATHEMATICAL MODELING AND FORMULATION OF VC PROCESSES

Mathematical Models for VC Processes

The complex physical and chemical processes involved in a vortexing combustor are shown schematically in Fig. A.1. These processes include: (a) turbulent vortexing gas flow with chemical reactions; (b) particle turbulent flow; (c) particle combustion; (d) radiative heat transfer. The modeling of VC processes consists of efforts for these four sub-models. Fig. A.2 gives the flow chart of these sub-models and their interactions. The present numerical work begins with the modeling of gas flow field.

Formulation of VC Gas Flow

The gas-phase equations, including momentum, energy, gas species equations, are rigorously derived for an axisymmetric confined strongly swirling and recirculating gas-particle flow with gas- and particle-phase combustions in cylindrical coordinates. Considerations of gas turbulence are also included in the formulation. In the implementation, a simplified turbulence model, which retains the basic features of strong swirling flows, should be used to reduce the computer storage requirement and to simplify the complexity in specifying boundary conditions. The CPU time and corresponding costs for numerical simulation can be greatly reduced. The gas-phase equations for axisymmetric gas-particle vortex flow with particle-phase and gas-phase combustion in cylindrical coordinates are finally expressed in the following generalized form:

$$\frac{\partial}{\partial z}(\rho u \varphi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v\varphi)=\frac{\partial}{\partial z}\left(\Gamma_{\varphi z}\frac{\partial \varphi}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_{\varphi r}\frac{\partial \varphi}{\partial r}\right)+S_\varphi+S_{p\varphi}$$

where ρ is gas density, φ denotes the generalized dependent variable, $\Gamma_{\varphi z}$, $\Gamma_{\varphi r}$ stand for the transport coefficients of φ, S_φ is the source term of gas phase itself, and $S_{p\varphi}$ is the source term due to gas-particle interactions (mass, momentum, and energy interactions). For different equations φ, $\Gamma_{\varphi z}$, $\Gamma_{\varphi r}$, S_φ, and $S_{p\varphi}$ are given in Tables A-1, A-2.

Table A-1 Variables and terms in gas-phase equations

Equation	φ	$\Gamma_{\varphi z}$	$\Gamma_{\varphi r}$	S_φ	$S_{p\varphi}$
Continuity	1	0	0	0	$S=-\Sigma n_k \dot{m}_k$
z-Momentum	u	$2\lambda\frac{k}{\varepsilon}\overline{u'u'}\rho$ $+2\mu$	$\lambda\rho\frac{k}{\varepsilon}\overline{v'v'}$ $+\mu$	$-\frac{\partial p}{\partial z}-\frac{\partial}{\partial z}[\frac{2}{3}(1-\lambda)\rho k$ $-2\lambda\rho\frac{k}{\varepsilon}\overline{u'v'}\frac{\partial u}{\partial r}]$ $+\frac{1}{r}\frac{\partial}{\partial r}(-r\lambda\rho\frac{k}{\varepsilon}\overline{u'w'}\frac{w}{r})$	$\Sigma\frac{n_k m_k}{\tau_{rk}}(u_k-u)+$ $+uS$
r-Momentum	v	$\lambda\rho\frac{k}{\varepsilon}\overline{u'u'}$ $+\mu$	$2\lambda\rho\frac{k}{\varepsilon}\overline{v'v'}$ $+2\mu$	$-\frac{\partial p}{\partial r}+\frac{\partial}{\partial z}(\mu\frac{\partial u}{\partial r})-2\mu\frac{v}{r^2}$ $+\rho\frac{w^2}{r}+\rho\frac{\overline{w'w'}}{r}$ $+\frac{\partial}{\partial z}[\lambda\rho\frac{k}{\varepsilon}(\overline{v'v'}\frac{\partial u}{\partial r}-\overline{u'w'}\frac{w}{r})]$ $+\frac{1}{r}\frac{\partial}{\partial r}[-r\rho\frac{2}{3}(1-\lambda)k]$	$\Sigma\frac{n_k m_k}{\tau_{rk}}(v_k-v)$ $+vS$
θ-Momentum	w	$\lambda\rho\frac{k}{\varepsilon}\overline{u'u'}$ $+\mu$	$\lambda\rho\frac{k}{\varepsilon}\overline{v'v'}$ $+\mu$	$-\rho\frac{vw}{r}-\rho\frac{\overline{v'w'}}{r}$ $-\frac{w}{r^2}\frac{\partial}{\partial r}(r\mu)$ $+\frac{\partial}{\partial z}(\lambda\rho\frac{k}{\varepsilon}\overline{u'v'}\frac{\partial w}{\partial r})$	$\Sigma\frac{n_k m_k}{\tau_{rk}}(w_k-w)$ $+wS$

Table A-1 Variables and terms in gas-phase equations(continued)

<table>
<tr><th>Equation</th><th>φ</th><th>$\Gamma_{\varphi z}$</th><th>$\Gamma_{\varphi r}$</th><th>S_φ</th><th>$S_{p\varphi}$</th></tr>
<tr><td>Turbulent kinetic energy</td><td>k</td><td>$c_k \rho \frac{k^2}{\varepsilon} + \mu/\sigma_k$</td><td>$c_k \rho \frac{k^2}{\varepsilon} + \mu/\sigma_k$</td><td>$G_k - \rho\varepsilon$</td><td>$0$</td></tr>
<tr><td>TKE dissipation rate</td><td>ε</td><td>$c_\varepsilon \rho \frac{k^2}{\varepsilon} + \mu/\sigma_\varepsilon$</td><td>$c_\varepsilon \rho \frac{k^2}{\varepsilon} + \mu/\sigma_\varepsilon$</td><td>$\frac{\varepsilon}{k}(c_{\varepsilon 1} G_k - c_{\varepsilon 2} \rho \varepsilon)$</td><td>$0$</td></tr>
<tr><td>Mixture fraction</td><td>f</td><td>$c_f \rho \frac{k^2}{\varepsilon} + \mu/\sigma_f$</td><td>$c_f \rho \frac{k^2}{\varepsilon} + \mu/\sigma_f$</td><td>$0$</td><td>$0$</td></tr>
<tr><td>f-Fluctuation</td><td>g</td><td>$c_g \rho \frac{k^2}{\varepsilon} + \mu/\sigma_g$</td><td>$c_g \rho \frac{k^2}{\varepsilon} + \mu/\sigma_g$</td><td>$c_{g1} c_k \rho \frac{k^2}{\varepsilon}\left[\left(\frac{\partial f}{\partial z}\right)^2 + \left(\frac{\partial f}{\partial r}\right)^2\right] - c_{g2} \rho \varepsilon g/k$</td><td>$0$</td></tr>
<tr><td>Gas species</td><td>Y_s</td><td>$c_Y \rho \frac{k^2}{\varepsilon} + \mu/\sigma_Y$</td><td>$c_Y \rho \frac{k^2}{\varepsilon} + \mu/\sigma_Y$</td><td>$-w_s$</td><td>$\alpha_s S$</td></tr>
<tr><td>Gas enthalpy</td><td>h</td><td>$c_h \rho \frac{k^2}{\varepsilon} + \mu/\sigma_h$</td><td>$c_h \rho \frac{k^2}{\varepsilon} + \mu/\sigma_h$</td><td>$-Q_{rg}$</td><td>$\Sigma n_k Q_k + c_p T S$</td></tr>
<tr><td>Stress expressions</td><td colspan="5">$\overline{u'v'} = -\frac{2}{3}\lambda(1-\lambda)\frac{k^2}{\varepsilon}\left[1 + \lambda^2\left(\frac{k}{\varepsilon}\right)^2\left(\frac{\partial w}{\partial r}\right)\left(\frac{w}{r}\right)\right]^{-1}\frac{k^2}{\varepsilon}\frac{\partial u}{\partial r}$;
$\overline{u'w'} = \lambda\frac{k}{\varepsilon}\left(-\overline{u'v'}\frac{\partial w}{\partial r}\right)$; $\overline{v'w'} = \lambda\frac{k}{\varepsilon}\left(-\overline{v'v'}\frac{\partial w}{\partial r}\right)$;
$\overline{u'u'} = \frac{2}{3}(1-\lambda)k - 2\lambda\frac{k}{\varepsilon}\left(-\overline{u'v'}\frac{\partial u}{\partial r}\right)$;
$\overline{v'v'} = \frac{2}{3}(1-\lambda)k$;
$\overline{w'w'} = \frac{2}{3}(1-\lambda)k - 2\lambda\frac{k}{\varepsilon}\left[\overline{v'w'}\left(\frac{\partial w}{\partial r} - \frac{w}{r}\right)\right]$</td></tr>
<tr><td>Reaction rate</td><td colspan="5">$w_s = \min\left[w_{sA}, w_{sT}\right]$
$w_{sA} = B\rho^2 Y_F Y_{ox} \exp(-E/RT)$
$w_{sT} = c_R g^{\frac{1}{2}} \rho\varepsilon/k$</td></tr>
<tr><td>G_k</td><td colspan="5">$\overline{u'u'}\frac{\partial u}{\partial z} + \overline{u'v'}\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z}\right) + \overline{v'v'}\left(\frac{\partial v}{\partial r}\right) + \overline{u'w'}\frac{\partial w}{\partial z}$
$+ \overline{v'w'}\left[r\frac{\partial}{\partial r}\left(\frac{w}{r}\right)\right] + \overline{w'w'}\left(\frac{v}{r}\right)$</td></tr>
</table>

Table A-2 Constants in gas-phase equations

λ	C_k	C_ε	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	C_{g1}	C_{g2}	C_R	C_f	C_g	C_Y	C_h	σ_k
0.2	0.24	0.15	1.44	1.92	2.8	2.0	1.0	0.22	0.22	0.22	0.22	0.9

σ_ε	σ_f	σ_g	σ_Y	σ_h
1.3	0.9	0.9	0.9	0.9

In the above table, μ --- molecular viscosity, w_s --- reaction rate, Q_{rg} --- radiative heat transfer, α_s --- fraction of contribution of s species due to mass change, n_k --- particle number density, m_k --- particle mass, σ --- turbulent Schmidt number.

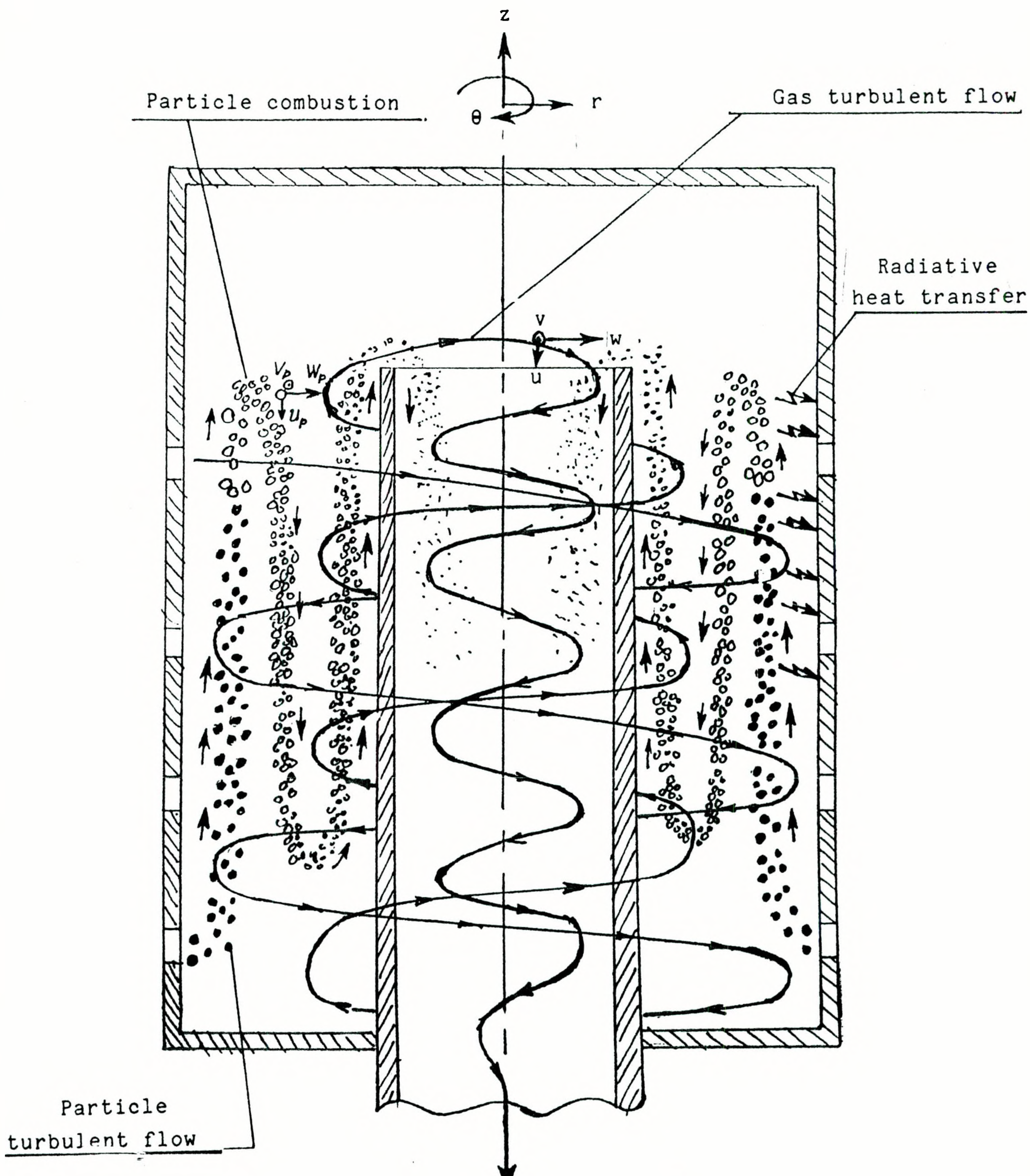


Fig. A1 The physical and chemical processes in Vortexing Combustors

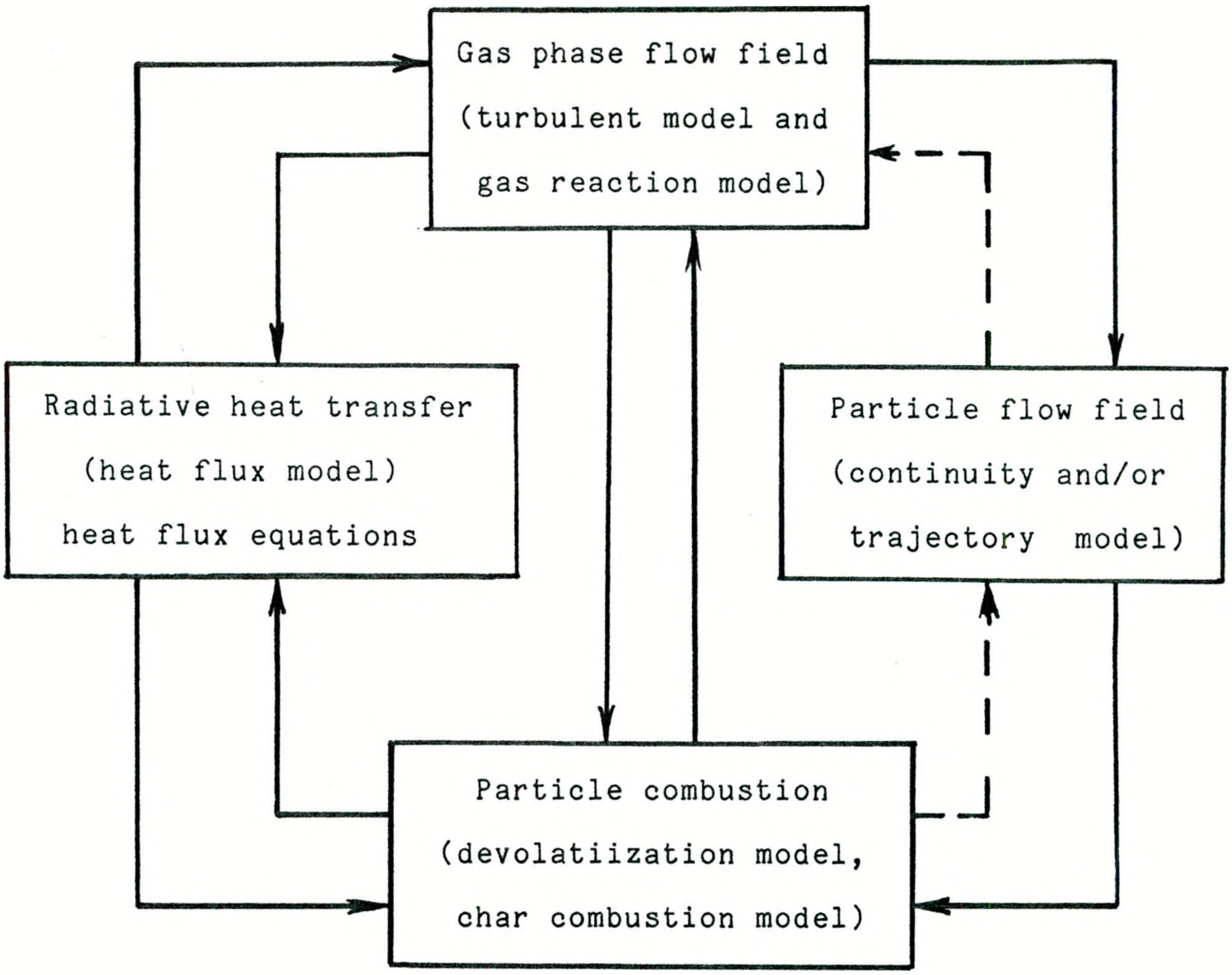


Fig. A2 The main parts of the VC modeling and their relations