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The bond graph simulation of steam turbine

#1R. R. Kulkarni, #2 S. A. Kulkarni

[1]kulkarnirohit139@gamil.com,

[2]sakulkarni.scoe@sinhgad.edu

#1Sinhgad College of Engineering- Mechanical Engineering Department, Savitribai Phule Pune University

#2Asso. Professor, Sinhgad College of Engineering,Mechnanical Engineering Department Savitribai Phule Pune University

ABSTRACT

The simulation for performance analysis using bond graph enables to mathematically model the system using power variables. The thermal process includes many complicated phenomenon and one of the example of complex phenomenon is steam turbine. The steam turbine is used to convert the pressure energy into the kinetic energy in the steam power plant. An impulse steam turbine is designed to operate between 5 bar to 1.25 bar pressure. The steam turbine is manufactured to demonstrate the charactistics of steam turbine. The bond graph model of the steam turbine involves thermal, hydraulic and rotational domain. The performance curves of turbine with boiler and brake just confirm the effectiveness and accuracy of bond graph modelling.

***Keywords*—Bond Graph Model, Steam Turbine**

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I. INTRODUCTION

The simulation is the imitation of the operation of a real-world process or system over time. The simulation is authoring the mathematical model of the system or process under study. Such models are usually one dimensional first order ordinary differential equations, which are solved with suitable numerical method. The accuracy of mathematical representation also defines the key characteristics or behaviors/functions of the selected physical or abstract system or process. The simulation is used to estimate the eventual real effects of influencing parameters and remedial courses of action. The simulation is also used when the real system is being designed but not yet built, or it simply does not exist. The key issues in simulation include acquisition of valid source information about the relevant selection of key characteristics and behaviours, the use of simplifying approximations and assumptions within the simulation, fidelity and validity of the simulation outcomes. The physical simulation refers to simulation in which physical objects are substituted for the real thing. The simulation in failure analysis refers to simulation to identify the cause of equipment failure in different conditions/environments [6, 7, 8].

The block diagram representation of any control system is very easy when it is single input and single output (SISO) control system. The powerful mathematical tools are available for design as well as analysis of linear control systems. In case of Multiple Input Multiple Output (MIMO) control systems, the block diagram representation goes little complicated and for analysis either signal flow graph method or Laplace Transforms Methods are used which are equally complicated and the computer routines are not possible from description of system to solution. The tools available are only helpful after the model is defined in statement or matrix form [3, 4, 5].

The simulation using Bond Graph is nothing but creating the mathematical model involving power variables. The Bond Graph simulation reduces all higher order, non linear, partial differential equations to simple sequential, linear first order ordinary linear differential equations. The power variables are those variables which multiplied gives power, e.g. voltage and current, pressure and volume rate of flow, etc. There are different softwares are used for bond graph simulation. Mostly CAMPG, MS 1, SYMBOLS Shakti, 20-Sim are used.

The main motive of the present work is to design steam turbine working between 5 bar and 1.25 bar atmospheric pressure and validate the results using bond graph software. The thermo-fluid system is discussed using schematic diagram and bond graph model in the literature survey. The section three presents the details of the design of the steam turbine and assembly of the steam turbine in detail. The section four presents the bond graph model of the steam turbine. The main focus of the dissertation is to simulate the steam turbine using bond graph model in 20-Sim software. The section five presents the experimental results and the simulation results and comparison between results. The section six presents conclusion deduced from the experimental results and simulated results.

II. LITERATURE REVIEW

The thermofluid processes are commonly encountered in process engineering. The main complexity of the thermofluid process is the result of the interaction of several areas of energy. The thermofluid systems involve mass transfer and thermal energy convection, and the coupling of the hydraulic and thermal power domain. Due to the strong nonlinearities in the thermofluid systems, the modelling is often complex, thus graphical modeling such as the bond graph tool becomes significant. The Bond graph language allows to deal with the enormous amount of equations describing the process behavior and to display explicitly the power exchange between the process components starting from the instrumentation architecture.

A. SIMPLE THERMO-FLUID SYSTEM [1]

A simple thermo-fluid system is shown in Fig 1. The level controller (LC) acts upon a pump to maintain a constant level of water in the tank. The water inside the tank is heated by using the thermal energy provided by the heater and the temperature is controlled by the temperature controller (TC). The valve at the output of the tank is used to deliver hot water to the consumer. The pump is considered as a flow source. The level sensor (L) and temperature sensor (T) are used to regulate the level and the temperature of the tank. The flow sensor (F) is used to measure the amount of water leaving the tank. The pressure sensor (P) at the bottom of the tank is a material redundancy to the level sensor (L=P/(ρg)).

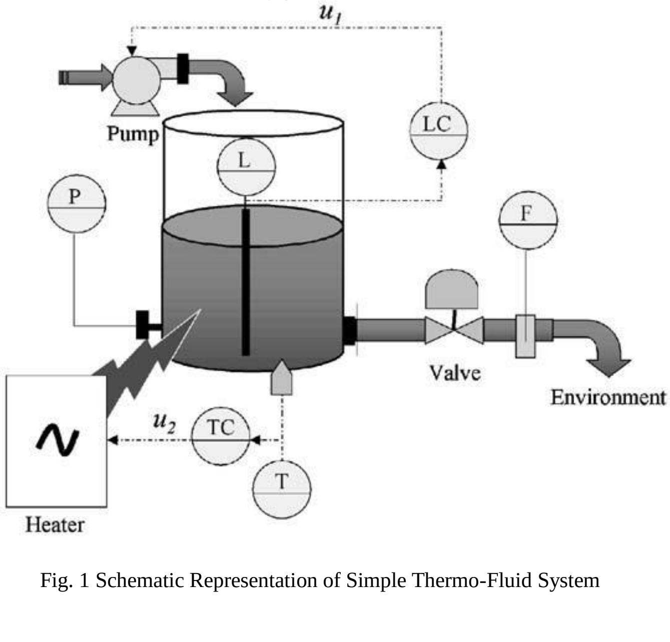

Fig. 1 Schematic Representation of Simple Thermo-Fluid System

B. THE BOND GRAPH MODEL [1]

The bond graph in pseudo thermal domain for the system is shown in Fig 2. The bond graph consists of different elements such as Se, MSf, C_t, R, C_h, CETF etc. The various elements are briefed discussed. The element MSf(23) represents heater i.e. supplied heat at constant rate. The controller consists of De:T i.e temperature sensor and TC i.e. temperature controller. The De:T supply temperature signal to temperature controller and temperature controller controls the temperature of the system. The 0 element gives temperature signal to De:T element and further goes to MSf via TC. The CETF element receives effort(T1) and signal(mdot). MSf(1) element represents a source of mass flow i.e pump. Element De:P denotes the pressure of system. Elements TF:ρg, 0, De:L, LC represents level controller system. When level of water exceeds limit, the signal is sent by element 0 to MSf via TF element. Elements C_t and C_h are represented by mC_p and A/g respectively. Element C_t receives signal from element 0 and effort from another element 0.

The different processes involved in the thermofluid processes are modeled using different bond graph elements such as Se, Sf, C etc in the simple thermo-fluid system. The deduction from literature survey is applied during bond graph modeling of steam turbine. The design of the steam turbine is discussed thoroughly in next section.

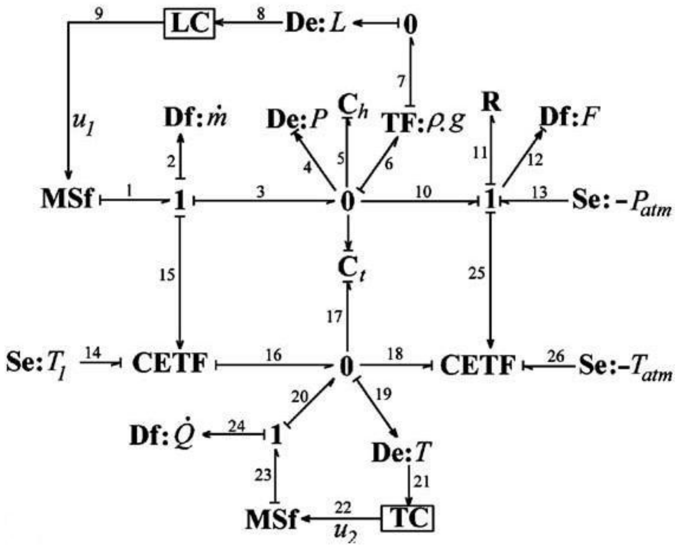

Fig. 2 Bond Graph Model of Simple Thermo Fluid System

III.DESIGN OF STEAM TURBINE

The design and manufacturing of the steam turbine is the main focus of the experimental work. The toughest and difficult most component to manufacture was blades with desired angles. The design of turbine includes the design of nozzle, blade, shaft and case in which turbine components to be enclosed. The input data for design of turbine depends upon the output of the boiler. The input data for steam turbine is as follows:

Power output: 200W
Turbine speed: 3000 rpm
Pressure at the inlet to the turbine: 5 bar,
Temperature at the inlet to the turbine 160°C
Back Pressure of steam: 1.25 bar.

As the required pressure drop is large, two stage steam turbine is designed for this experimental test rig. The isentropic heat drop (Δh_{isen}) is calculated on the basis of the inlet and the outlet conditions:
At the inlet: pressure 5 bar, h1 = 2764 kJ/kg;
At the outlet: pressure 1.25 bar, h2 = 2620 kJ/kg;
Δh = h1 – h2 = 2764 - 2620 = 144 kJ/kg
Assuming the losses in the regulating valve as 5%, the isentropic heat drop ($\Delta h'_{isen}$):
$\Delta h'_{isen}$ = 0.95 * 144 = 136.8 kJ/kg

The details of the design parameters are as discussed as follows. The pressure drops at first stage of the turbine and at second stage of the turbine are considered from 5 bar to 2.6 bar and 2.6 bar to 1.25 bar absolute respectively. The design of stator/nozzle depends upon the pressure drop occurring in it. The design parameters of the stator/nozzle are discussed as follows:

A. STATOR

The design of nozzle involves the calculation of inlet area, throat area, exit area, angle of convergence, angle of divergence, length of convergent portion, length of divergent portion, angle of inclination of nozzle at exit, thickness of nozzle, number of nozzles and pitch. The velocity at the exit of nozzle is calculated from

$$C_t = 44.72 * \sqrt{H'_{isen}}$$
$$C_t = 342\ m/s$$

The angle α_1 may be assumed between the limits of 14 to 20 degrees. The angle α_1 is assumed as 16°. For two row discs, u/C_1 may be taken from 0.05 to 0.2. Since C_1 is constant hence for each assumed value of u/C_1, the peripheral velocity is determined and velocity triangles are drawn for each value of u assuming β_2 and K. If the critical pressure is more than back pressure then, the nozzle is convergent. Using continuity equation at the section considered the area may be calculated as follows at inlet

$$A_1 * C_1 = \dot{m} * \vartheta_1$$

The mass flow rate is assumed as 0.01 kg/s. The area of the nozzle is : $A_1 = (\vartheta_1 * \dot{m})/C_1$

$$A = 11\ mm^2$$

The area may be adjusted by breadth and height as per type rectangular cross-section. The nozzle is short with well-rounded entrance edges allowing a good issuing jet. The length of convergent portion is calculated as follows for rectangular cross-section:-

$$tan(\theta_c/2) = (D_1 - D_2)/2L_c$$
$$L_c = 14\ mm$$

Where, Lc = length of convergent portion, θc = angle of convergence (25°)

The number of nozzle is selected on the basis on pitch circle diameter and pitch of nozzle (n = ΠD/S). The number of nozzle is calculated as 4. The steam enters onto the blade component. The blade/rotor is designed as follows.

B. Rotor

The function of the rotor is to change the direction of the high velocity steam and hence the momentum of the jet or jets of steam and so produce a force which propels the blades. The mean blade diameter is 100mm and the height of the blade on the rotor is adjusted as per requirement. It is essential to draw the diagrams showing the variations of velocity of steam during its flow through the blade passages. The velocity diagram is shown in the fig 3. For first stage rotor design, input data is as follows:
α1 = β2 = 16°; α1= β1 = 18°; C1 = 342 m/s (from nozzle);
Cf1 = C1 * sin (α1) = 94.2 m/s;
Cr1 = Cf1/sin (β1) = 304.8 m/s;
Cr2 = C1= 341.77 m/s;
C2 = ((sin (β2) / sin (α2)) * Cr2) = 304.8 m/s;
Cf2 = (sin (α2) * C2) = 94.2 m/s; u = 71m/s;
Cw = Cw1 + Cw2 = 618.5 m/s;

$$P = (\dot{m} * C_w * u)/1000$$
$$P = 239\ W$$

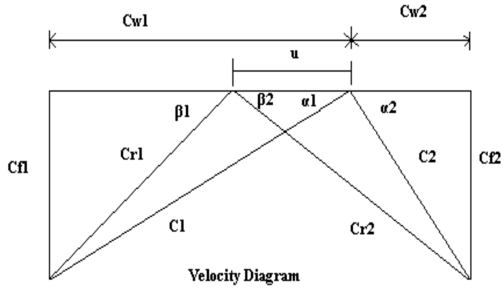

Fig 3 Velocity Diagram of Steam Turbine

For second stage of the turbine, same calculations are done and values are calculated.
α1 = α2 = 16°; β1 = β2 = 18°; C1 = 447.2 m/s;
Cf1 = C1 * sin (α1) = 123.6 m/s;
Cr1 = Cf1/sin (β1) = 398.8 m/s;
Cr2 = K * Cr1 = 359 m/s;
C2 = ((sin (β2) / sin (α2)) * Cr2) = 402.4 m/s;
Cf2 = (sin (α2) * C2) = 110.9 m/s; u = 71m/s;
Cw = Cw1 + Cw2 = 123.2m/s;

$$P = (\dot{m} * C_w * u)/1000$$
$$P = 88\ W$$

The average power generated by the dynamometer is 150 W. The power generated is very low, so eddy current dynamometer is designed for power measurement purpose. The turbine assembly includes the outer covering, inlet and outlet of steam, space for steam travel. The different aspects of the steam turbine are discussed as follows.

C. Turbine Assembly

The fig 4 shows the assembly of the steam turbine. The overall dimension of the steam turbine block depends upon the dimensions of the stator, the rotor and the space required for steam passage and expansion. The overall dimension of the block is 138 mm by 120 mm. The housing is used for the steam entry and exit. The turbine assembly is mounted on the single shaft. The shaft is coupled to the eddy current dynamometer for power measurement.

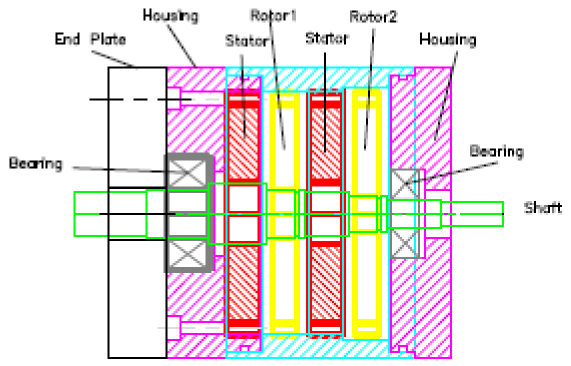

Fig 4 Assembly of Steam Turbine

IV. BOND GRAPH MODEL OF STEAM TURBINE

The bond graph model of steam turbine involves three domain i.e. thermal, hydraulic and rotational domains. The steam at the inlet of the turbine has 5 bar pressure and 150 C superheated. So there are two domain input to turbine. First input is thermal domain i.e. effort = temperature and flow = enthalpy. Second input is hydraulic domain i.e. effort = pressure and flow = mass flow rate. The steam turbine is made up of two parts stator and rotor. The pressure drop occurs in the stator and velocity of the steam increases. The steam passes through blades which rotates the shaft. The turbine shaft is coupled with eddy current dynamometer in the experimental test rig.

The three domains should be separately shown as domain mixing is not allowed in the bond graph. Element Sf1 and Sf2 are input to turbine in the thermal and hydraulic domain respectively. Element Se1 and Se2 are output of the turbine in the thermal and hydraulic domain respectively.

Sf1

The element Sf1 represents thermal domain i.e. enthalpy input to the turbine. output.e is enthalpy input and output.f is the temperature of the steam. It has fixed flow out causality. An enthalpy of the steam at 5 bar pressure and 160°C is 2743 kJ which is given as input to turbine model.

```
parameters
        real C = 2743;    // output value
variables
        real effort;
equations
        output.f = C;
        effort = output.e;
```

Sf2

An element Sf2 represents hydraulic domain i.e pressure input to turbine. output.e is pressure input to turbine and output.f is mass flow rate. It has fixed flow out causality. 5 bar atmospheric pressure is given as input in the hydraulic domain to the turbine model.

```
parameters
        real C = 5.0e5;    // output value
variables
        real flow;
equations
        output.e = C;
        flow = output.f;
```

Se1

An element Se1 represents thermal domain i.e. temperature input to turbine. output.e is temperature and output.f is enthalpy. It has fixed effort out causality. The temperature of steam at outlet of the turbine is 423K.

```
parameters
        real C = 423;    // output value
variables
        real flow;
equations
        output.e = C;
        flow = output.f;
```

Se2

An element Se2 represents hydraulic domain i.e. mass flow rate as input. output.f represents mass flow rate and output.e represents pressure of the steam. It has fixed effort out causality. The mass flow rate of the steam is 0.01 kg/s.

```
parameters
        real C = 0.01;    // output value
variables
        real effort;
equations
        output.f = C;
        effort = output.e;
```

Submodel1

The Submodel1 represents the thermal domain of the steam turbine. The submodel1 has one input port p1 and one output port p2. p1.f and p2.f represents the enthalpy of the steam at the inlet and outlet of the turbine respectively. p1.e and p2.e represents the pressure of the steam at the inlet and outlet of the turbine respectively. c1 represents the velocity of the steam. The velocity of the steam increases due to pressure drop in the nozzle.

```
parameters
        real x = 0.98;
        real hf = 546.2;
        real hfg = 2173.7;
equations
        p2.f = hf + (x * hfg);
        c1 = 0.95 * 44.72 * sqrt(p1.f - p2.f);
        p1.e = p2.e;
```

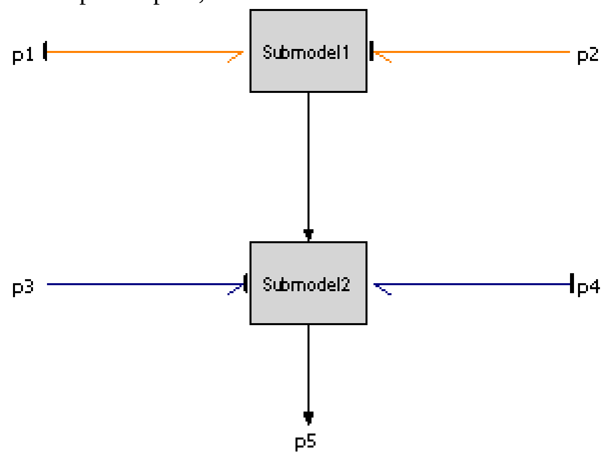

Fig 5 Bond graph of sub-component in the turbine

Submodel2

The submodel2 represents the hydraulic as well as rotational domain. The submodel2 has one input port and two output ports. The input port p3 and output port p4 has hydraulic domain and p5 has rotational domain. The input port p3 and output port p4 has indifferent causality. The output port p5 has fixed angular velocity causality.

```
parameters
        real alpha1 = 0.2792;
        real beta1 = 0.3141;
        real alpha2 = 0.3141;
        real beta2 = 0.2792;
        real vg = 0.6684;
        real x = 0.98;
        real K = 0.9;
        real D = 0.1;
variables
        real v1, a2, d1, d2;
        real thetaD, len;
        real cf1, cr1, cr2, c2;
        real u, n, cw, P;
equations
        p4.e = 0.52 * p3.e;
        p3.f = p4.f;
        v1 = x * vg;
        a2 = (p4.f * v1) / c1;
        d2 = sqrt( a2 / (3.14 * 4));
        d1 = 0.01;
        thetaD = 0.436;
        len = (d1 - d2)/(2 *tan(thetaD/2));
        cf1 = c1 * sin(alpha1);
        cr1 = cf1 / sin(beta1);
        cr2 = K * cr1;
        c2 = (sin(beta2)/sin(alpha2))*cr2);
        u = ((cos(alpha1) * c1) –((cos(beta1) * cr1));
        n = (u * 60) / ( 3.14 * D);
        p5.f = (2 * 3.14 * n)/60;
        cw = (( cos(beta1) * cr1) + (cos(beta2) * cr2));
        P = p4.f * cw * u;
```

The bond graph model of the steam turbine made by using elements which is discussed above is shown in fig 6.

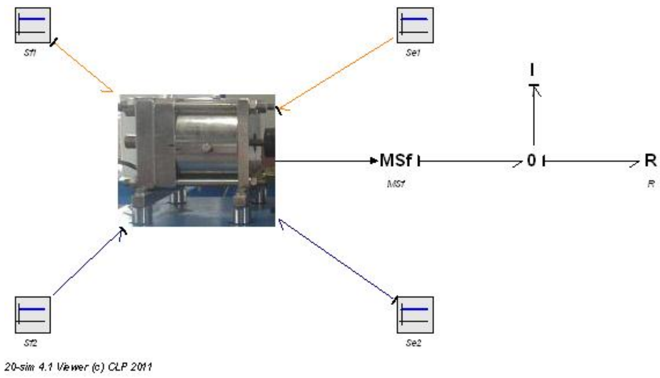

Fig 6 Bond Graph Model of Steam Turbine

V. EXPERIMENTAL AND SIMULATED RESULTS

The experimental test rig is shown in fig 7. The experimental test rig consists of boiler, steam turbine and eddy current dynamometer. The experimental and simulation results are discussed here.

Figure 7 Experimental Test Rig of Steam Turbine

The boiler provides steam having 5 bar pressure and 160°C temperature. The mass flow rate of the steam is 0.01kg/s. The shaft of the steam turbine is coupled with eddy current dynamometer to measure the power. The mass of the steam enters the nozzle. The pressure of the steam is reduced in the nozzle and its velocity is increased. The increased velocity is utilized to rotate the blades of the turbine. The rotor blades rotate the shaft on which it is mounted. The readings shown in the display are as follows:

Sr. No.	Pressure at inlet (bar)	Pressure at outlet (bar)	Temperature at inlet (C)	Speed of shaft (rpm)
1	5	1.25	160	7500

Table 1 Observation Table

Simulation Results:

The bond graph model of the steam turbine as shown in fig 5 is simulated in 20Sim software and simulated results are as follows:

The graph of angular velocity vs time is shown in the fig 7. The angular velocity of the shaft increases from zero and comes to steady conditions after sometime due to inertia of the components which are mounted on the shaft.

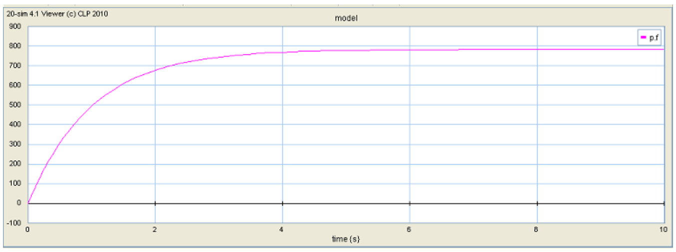

Fig 7 Plot of angular velocity vs time

VI. CONCLUSIONS

a The thermal process is mapped using elements of the bond graph software. The experimental results are compared with the simulation results. They show satisfactory accuracy. The future scope involves the bond graph simulation of steam power plant processes with experimentation.

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