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Flow instability due to cryogenic cavitation in the downstream of orifice †

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Abstract

Flow instability in LRE (liquid rocket engine) occurs due to various reasons such as flow interactions with valve, orifice and venturi, etc. The inception of cavitation, especially in the propellant feeding system, is the primary cause of mass and pressure oscillations because of the cyclic formation and depletion of cavitation. Meanwhile, the main propellant in a liquid rocket engine is the cryogenic fluid, which properties are very sensitive to temperature variation. And the change of propellant properties to temperature variation by thermodynamic effect needs to be properly taken into account in the flow analysis in order to understand basic mechanisms for cryogenic cavitation. The present study focuses on the formation of cryogenic cavitation by using the IDM model suggested by Shyy and coworkers. The flow instability was also numerically investigated in the downstream of orifice with a developed numerical code. Calculation results show that cryogenic cavitation can be a primary source of flow instability, leading to mass fluctuations accompanied by pressure oscillations. The prediction of cavitation in cryogenic fluid is of vital importance in designing a feeding system of an LRE.

Keywords: Cryogenic fluid; Cavitation; Flow instability; Orifice

1. Introduction

The feeding system of a liquid rocket engine (LRE) consists of various flow control devices such as venturi, valves, orifices and pipe connections. The flow in the system may experience unstable fluctuations due to the formation of cavitation, turbulent flow and flow separation. The flow instability in turn results in the destructive damage to structures, even total collapses. Cavitation in the feeding system is found to be one of the undesirable phenomena because it induces flow instability through the cascade of production and depletion of pressure bubbles in the flow and deteriorates system performance. Also, the vaporized gas occupying a volume almost 37 times larger than liquid may reduce the effective flow area in the feeding system. This blocks mass flow rate to pass through less than design value. Engine performance can thus be affected by the reduced amount of propellant in the feeding system. In this regard, the prediction of the formation of cavitation in the feeding system is of critical importance in determining engine performance and in assessing the flow instability in LRE. Most LRE systems utilize cryogenic propellants such as liquid oxygen or liquid hydrogen. The cavitation in cryogenic fluid differs from that observed in conventional liquids such as water.

The main differences of cavitation in cryogenic fluid lie in the temperature sensitivity and temperature dependence on the formation of cavitation. Since the phase change from liquid to vapor requires heat from surrounding fluids, the temperature inside cavitations

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surrounded by cryogenic fluid becomes lower than the liquid temperature. This is called "thermodynamic effect" in cryogenic cavitation [1-4]. Due to the thermodynamic effect, the vapor pressure in the cavitation becomes less than that without thermodynamic effect. This is the reason why cavitation size in cryogenic fluids is relatively small compared to the size formed in conventional fluids [2]. The temperature sensitivity of cryogenic cavitation attributes to the physical features that vapor pressure in cryogenic fluid is quite sensitive to temperature variations. Thus, it is more difficult to predict the cavitation in cryogenic fluids than in conventional fluids because the prediction should take into account the variation of thermodynamic properties being sensitive to temperature change. This requires the energy equation in governing equations to accommodate the thermodynamic effect in the formation of cavitation.

There are two well known methods of numerical simulation for production and depletion of cavitation. The first one is the method using the Rayleigh–Plesset equation, which describes the time evolution of cavitation nuclei growth when the pressure becomes lower than vapor pressure. This modeling has advantages in depicting the production and extinction of each bubble in detail. However, it may be burdensome in using computational resources and has convergence problems in dealing with the problems where vapors dominate in volume ratio. Thus, this modeling is not suitable for calculating shallow cavitation layers around turbo pump inducer or pump blade.

Another method for calculating cavitation resorts to the phase transport equation. The production and extinction of cavitation can be simulated by condensation and evaporation of fluid. However, this method is not good at predicting the production and depletion of every bubble in the flow. The main advantages, though, are good convergence, simple implementation, and easy application to various types of cavitation problems. Thus, the modeling with phase transport equation was adopted in the present study. The phase transport equation suggested by Merkle [5] and Kunz [6] is the equation describing the phase boundary in terms of two different velocities in each phase. This equation is capable of predicting the boundary very well if two phases are separated definitely.

In a cryogenic fluid, the formation of cavitation deprives heat from the surrounding fluid due to thermodynamic effect and the phase boundary becomes confined into a narrow region filled with frosty particles. Thus, the prediction of cavitation in cryogenic fluid mainly depends on how efficiently the model can simulate and capture the frosty boundary. Shyy et al. resolved the difficulty of frosty boundary in cryogenic cavitation by suggesting MUSHY IDM method [3]. This modeling takes boundary region into account in numerical modeling instead of definite boundary used in the calculation for conventional cavitation. So, the model with a frosty boundary can capture in the calculation and it shows better agreement with experimental data than Merkle's model [3].

The present study is primarily concerned with the prediction of cavitation in cryogenic fluid and its flow instability in the downstream of the orifice. To this end, the numerical calculation for the prediction of cavitation has been done with a developed code implemented with Shyy's cavitation modeling and MUSHY IDM boundary treatment. A developed code verified its validity and accuracy by the comparison of results with experimental data. Various orifice configurations are selected to investigate the effect of orifice shape on the flow instability. Calculation results are also compared to investigate the effect of configuration on the generation of cavitation and flow instability in the downstream.

2. Governing equations

A couple of modeling efforts have been implemented with governing equations: continuity, momentum equations, and volume fraction transport equation in the Cartesian coordinate system. The governing equations are as:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial(\rho_m u_j)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho_m u_j)}{\partial t} + \frac{\partial(\rho_m u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial k_j} + \frac{\partial}{\partial x_i}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)\right] \tag{2}$$

$$\frac{\partial}{\partial t}[\rho_m(h + f_v L)] + \frac{\partial}{\partial x_j}[\rho_m u_j(h + f_v L)] = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\mathrm{Pr}_L} + \frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial h}{\partial x_j}\right] \tag{3}$$

$$\frac{\partial \alpha_l}{\partial t} + \frac{\partial(\alpha_l u_j)}{\partial x_j} = m + m \tag{4}$$

A mixture density is defined by the summation of liquid density and vapor density associated with volume fraction coefficient α_l. Here f_v is vapor mass fraction, h and ρ_m denote enthalpy and mixture density, respectively. Following are definitions of these variables.

$$f_v = \frac{\rho(1-\alpha_l)}{\rho_m}, \qquad h = C_p T, \tag{5}$$
$$\rho_m = \rho_l \alpha_l + \rho_v (1-\alpha_l)$$

Subscript l represents liquid, v is for vapor and t means term for turbulent. Also, m is for mixture. And Cp and T are specific heat at constant pressure and temperature, respectively. A conventional k-e turbulence model was used in the calculation.

2.1 Cavitation modeling

Numerical calculation uses a cavitation modeling of MUSHY IDM (interfacial dynamics model) suggested by Shyy et al. to account for unique features of cryogenic fluid. As previously mentioned, this modeling assumes the region inside cavitation is occupied by a mixture of liquid and vapor and the phase change occurs through a thin bi-phasic region. Thus, mass conservation and momentum transfer between liquid and a mixed region can be expressed as Eq. (6)

$$m^- = \frac{\rho_l MIN[0, p-p_v]\alpha_l}{\rho_-(U_{m,n}-U_{I,n})^2(\rho_l-\rho_v)t_\infty},$$
$$m^+ = \frac{\rho_l MAX[0, p-p_v](1-\alpha_l)}{\rho_+(U_{m,n}-U_{I,n})^2(\rho_l-\rho_v)t_\infty}$$
$$\frac{\rho_l}{\rho_-} = \frac{\rho_l}{\rho_v} + \left(1.0 - \frac{\rho_l}{\rho_v}\right)^{\exp^{-(1-\alpha_l)/\beta}}, \qquad \frac{\rho_l}{\rho_+} = \frac{\rho_l}{\rho_m} \tag{6}$$

Here, $U_{m,n}$ is a normal component of velocity vector in a mixed region and U_{Ln} is a normal component of velocity vector on the boundary surface. Note that b is a free parameter. Reference [2] has details for the modeling. The numerical simulation requires an energy equation to take thermodynamic effect into account in the formation of cavitation in a cryogenic fluid. It is worth noting that flow works and viscous energy dissipation are neglected in source terms of energy equation since these are assumed to have negligibly small influence in dealing with the inception of cavitation in cryogenic flow. Energy Eq. (3) can be further simplified by using relations of mixture density and mass ratio defined in Eq. (5). Final form of the energy equation becomes

$$\frac{\partial}{\partial t}[\rho_m(h)] + \frac{\partial}{\partial x_j}[\rho_m u_j(h)] =$$
$$\frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\Pr_L} + \frac{\mu_t}{\Pr_t}\right)\frac{\partial h}{\partial x_j}\right] + \rho_v L(m^+ + m^-) \tag{7}$$

It is obvious that energy Eq. (7) includes terms of production and depletion of cavitation as sources of energy change in phase transport equation. Thus, numerical solutions need to treat temperature drops in cavitation region due to evaporation cooling of cryogenic fluid with Eq. (7).

Meanwhile, material properties in cryogenic fluid are quite more sensitive to temperature variations than to pressure variations. Table 1 summarizes the temperature dependency of each property such as latent heat, density, viscosity and vapor pressure of liquid hydrogen. Reference [8] shows more detailed information of material properties and dependency on temperature variations in various cryogenic fluids.

For the numerical scheme, a conventional finite volume method implemented with the SIMPLE algorithm was used. And the collocated grid system was also used for allocation of velocity components u, v and dependent variables. The calculation utilizes the SIMPLE algorithm, and convective terms can be differenced by upwind scheme in the grid system. Details of the numerical schemes are found in ref. [7].

2.2 SOS (Speed of Sound) modeling

The formation of cavitation produces a mixture

Table 1. Temperature dependency of properties in LH2.

Latent Heat	$L = \frac{dP_v}{dT}(V_v - V_l)T$
Density (g/ml)	$\rho_L = A \cdot B^{-(1-T/T_c)^n}$
	A=0.43533, B=0.28772, n=0.29240, Tc=154.58
Viscosity (cp)	$\log_{10}\mu_L = A + B/T + C\cdot T + D\cdot T^2$
	A=-5.0957, B=1.7983E2 C=3.9779E-2, D=-1.4664E-4
Vapor Pressure (mmHg)	$\log_{10} P = A + B/T + C\log_{10} T + D\cdot T + E\cdot T^2$
	A=20.6695, B=-5.2697E2, C=-6.7062, D=1.2926E-2, E=-9.8832E-13

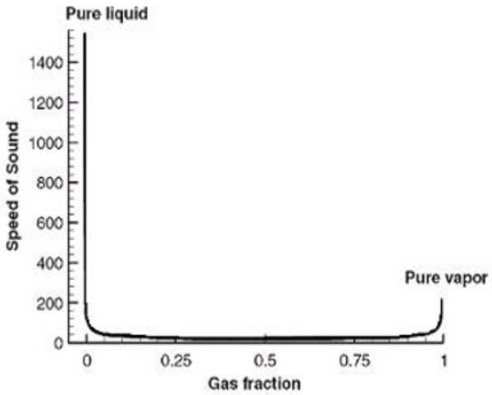

Fig. 1. Speed of Sound in pure liquid, vapor, and mixture region [3].

phase region where liquid and vapor coexist. The speed of sound in this region is much lower than that observed in single phase regions, as shown in Fig. 1.

The mismatch of the speed of sound comes from the density variations in the mixture region. A calculation with pressure-based algorithms requires methods to compensate density variations due to pressure changes and the density changes in mixture region. SOS modeling is the method to take additional density changes in the mixture region into account in the numerical calculation [3]. Eq. (8) shows a relation used for the compensation of density variations with the implementation of SOS modeling.

$$\rho' = C(1-\alpha_l)P' \tag{8}$$

Here C is an arbitrary constant that is determined by experience as an order of O(1) quantity since larger C induces an unstable convergence feature by changing the convergence trajectory during the calculation.

3. Numerical calculations

3.1 Code validation

Numerical calculations were done to assess code validity and the accuracy by comparing numerical results with experimental data for orifice cavitations [9]. The configurations of orifice and numerical calculation conditions are the same as shown in reference [9]. A rectangular duct with 2mm in diameter, 15mm of inlet diameter is used in calculation. Grid points are 150x80, and liquid nitrogen (LN2) is a working fluid having initial pressure and temperature of 77.2 K and 0.239 MPa, respectively. Reynolds number is fixed as 2.21E5.

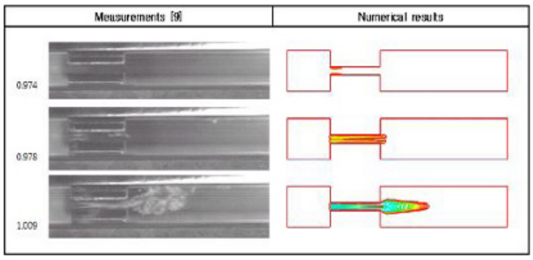

Fig. 2. Validation checking of developed code by the comparison with experimental data.

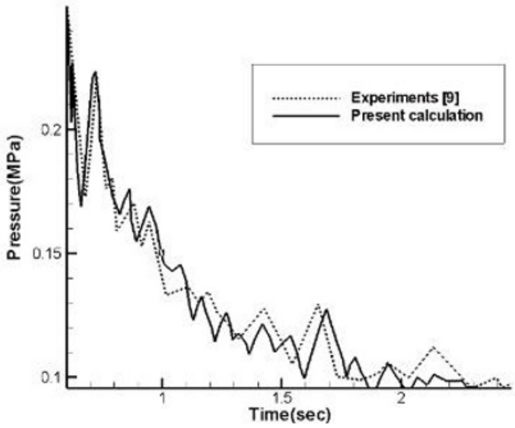

Fig. 3. Comparison of pressure oscillations with measurements.

Fig. 2 shows the comparison of calculation results of evolution of cavitation with experimental data [9]. The inception of cavitation is found as small bubbles at the front edge of the orifice. The bubble becomes larger and is being stretched to downstream and finally passes through the orifice. Numerical results show qualitatively a very good agreement with photos capturing the evolution of cavitation through the orifice.

Pressure fluctuations were compared with experimental measurements to investigate flow instability caused by the formation of cavitation in the downstream. The inception of cavitation starts at the edge of the orifice due to velocity increase and pressure drop. As seen in the figure, the shape of cavitation elongates and collapses periodically in the downstream even though the production of cavitation continues to occur at the orifice edge. The cyclic behavior of production, growth and collapse of cavitation dominates at the orifice and in the downstream. This can trigger pressure fluctuations resulting in flow instability in the downstream of orifice.

Fig. 3 compares calculation results of pressure fluctuations with experimentally measured data in the downstream. Results show a very good agreement with measured data.

3.2 Flow instability in various orifice configurations

In numerical calculations, flow instability was investigated with various orifice configurations focusing on the pressure fluctuations in the downstream. Fig. 4 shows the configuration of orifices used in the calculations. Case A is the same orifice as in reference [10] selected as a baseline one to compare the numerical accuracy of calculation with experimental data. Cases B and C are chosen with modifications from orifice shape A, as shown in Fig. 4. Numerical calculations focus on the effect of orifice shape on the formation of cavitation and pressure oscillations, which may result in the flow instability.

The calculation conditions can be summarized as follows: liquid hydrogen as a working fluid, temperature of 21.7K, and vapor pressure of 1.475 bar (21.755 Psia) at inlet. The mass flow rate is fixed as 130 lbm/sec and inlet pressure is 1.0E6 Pa. Orifice diameter is set as 0.1524m from reference [10]. Also, grid points are made with 246x80 in the calculation.

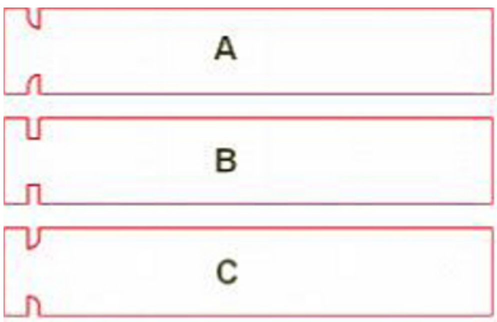

Fig. 4. Configurations of orifice selected for calculation.

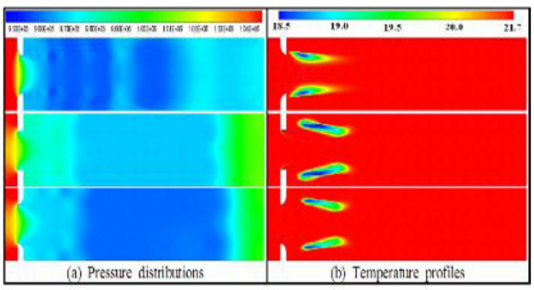

Fig. 5. Pressure and Temperature profile in the downstream of selected orifice.

Fig. 5 shows the pressure and temperature distribution in the downstream of the orifice when the cavitation developed at the orifice. Pressure oscillations in case A seem to be different from other cases in that the frequency of oscillation is higher and the amplitude is smaller than those observed in cases B and C. This means that the cavitation in case A is not strong enough to induce big pressure amplitude in the downstream. Fig 5-b also confirms that the temperature difference inside cavitation in case A is relatively less than other cases even though temperature differences are nearly 3K in all cases.

Fig. 6 shows the time evolutions of cavitation in each orifice case. Since the calculation did not account for the gravitational effect, results in Fig. 6 show a perfect symmetry over the centerline of the orifice. In reality, the shape of cavitation will bend upward in the flow due to buoyancy force. As expected, cases B and C show similar patterns of evolution showing the breakup in the middle of cavitation with elongated shape. However, the pattern in case A differs from other cases in that flow passes through orifice A without making secondary fluctuations and breakups around cavitation and shows a relatively short cavitations in length. Thus, it can be summarized that the flow smoothly passing through the orifice has a tendency of reluctance to yield big and strong cavitations.

The cyclic behavior of production and extinction of cavitations in the flow can trigger pressure oscillations in the downstream of the orifice, leading to mass flow fluctuations. This is of critical importance in predicting the thrust performance and assessing combustion instability in an LRE system because mass flow rate is directly related to the amount of thrust generated in the rocket. Thus the primary concern of the present study is to predict and estimate the effect

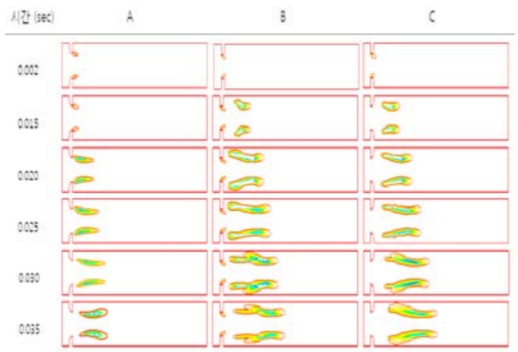

Fig. 6. Time evolutions of cavitation in each orifice case.

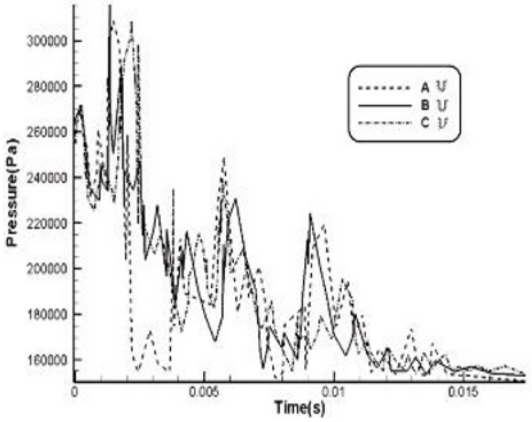

Fig. 7. Trace of Pressure Fluctuations at 5 inch from orifice.

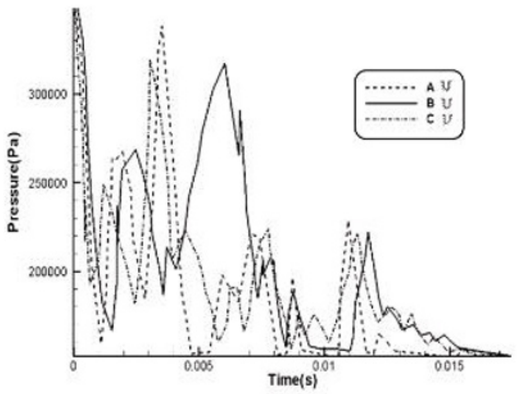

Fig. 8. Trace of Pressure of Fluctuations at 10 inch from orifice.

of orifice configurations on pressure oscillations and mass flow fluctuations when cavitations are formed in the cryogenic propellant flow.

Fig. 7 and 8 show numerical trajectories of pressure oscillation at different locations of 12.7cm(5 inch) and 25.4cm (10 inch) from orifice, respectively. As seen in Fig. 7, the pressure oscillations in case A show relatively small amplitude compared to other cases even though the overall behavior of amplitudes decreases monotonically in time. In Fig. 8, all cases show quite large amplitudes in oscillation compared to the amplitude in Fig. 7. This is due to the partial depletion of cavitations and pressure recovery near this location. Depletion of cavitation could produce large pressure perturbations in the flow. The pressure oscillations can be transferred to structural vibrations or lead to total damage sometimes and trigger combustion instability.

Fig. 9 shows the oscillations of propellant mass flow measured at 5 inches from orifice. In the calculation, input mass flow rate is fixed as 130lbm/sec if cavitations are not formed in the flow. However, the generation of cavitations may reduce the amount of propellant mass passing through the orifice by blocking the effective flow passage with cavitation vapors, since cavitation vapors in cryogenic fluid can occupy almost 37 times larger volume in the flow. This is the main reason why mass flow rate is reduced and fluctuated in the downstream. The calculations in Fig. 9 show that the maximum value of oscillations is about 30 to 35 lbm depending on the configuration of orifices. Since the present calculation did not account for viscous dissipation in energy equation, calculation results may show some exaggerations in oscillation amplitude. Nonetheless, the oscillation of mass flow rate in the downstream to the combustion chamber is not desirable and should be avoided by all means. If this happens, combustion instability or structural damages are inevitable during the operation. In this sense, the prediction of cavitations and assessment of flow instability of cryogenic fluid flow are of critical importance in the design of feeding system of the LRE.

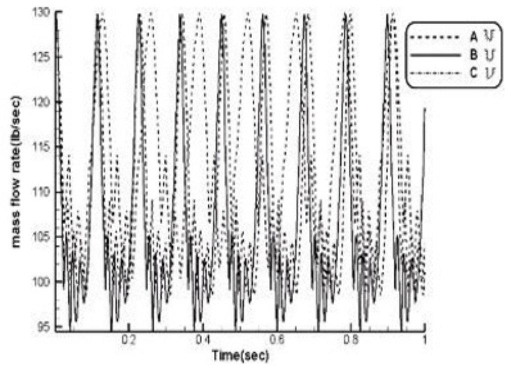

Fig. 9. Trace of mass flow fluctuations at 5 inch from orifice.

4. Conclusions

This paper focuses on the numerical simulation for cavitations in cryogenic fluid and investigates the effect of orifice configuration on the flow instability due to cavitation formation in the downstream. Cavitation modeling for cryogenic fluid requires additional treatments by taking thermodynamic effect into account in the energy equation proposed by Shyy et al. The accuracy and validity of a developed code were checked by the comparison of calculation results with experimental data. Also, numerical calculations were conducted to predict mass flow fluctuations and simulate flow instability in the downstream of orifice with several selected orifice configurations. Results show a very good agreement with experimental data. Also, results for several orifice configurations show that mass flow fluctuations are strongly dependent on the behavior of production and depletion of cavitations since cavitations may reduce the effective flow passage. Orifice configurations of case B and C were found to produce more severe pressure oscillations than case A because the size and length of cavitation in case A are adequately small compared to other cases. And time evolution of cavitations in the downstream of an orifice can provide a guideline to determine the efficient orifice shape generating less severe flow instability. Thus, it can be summarized that the prediction of cavitations in cryogenic fluid is of vital importance in estimating the performance of feeding system and LRE in the preliminary design stage.

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