Formulation of Field Data Based Model for Productivity Enhancement of Filament Winding of Composite Pressure Vessel Manufacturing –A Mathematical Approach

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Abstract— **The paper describes an approach for formulation of generalized field data based model for the process of filament winding. The theory of experimentation as suggested by Hilbert Schenck Jr. is applied. It suggests an approach of representing the response of any phenomenon in terms of proper interaction of various inputs of the phenomenon. The filament winding of tube/ pressure vessel made up of glass fiber reinforcement is considered for study which is a complex phenomenon.**

The aim of field data based modeling for filament winding process is to improve the performance of system by correcting or modifying the inputs for improving output. The reduction of human energy expenditure while performing axle assembly is main objective behind study. Reduced human energy consumption will increase overall productivity of assembly process. The work identifies major ergonomics parameters and other workstation related parameters which will affect the productivity of axle assembly process. The identified parameters are raw material dimensions, workstation dimensions, energy expenditure of workers, anthropometric data of the workers and working conditions. Working conditions include humidity of air, atmospheric temperature, noise level, intensity of light etc. at workstation which influence the productivity of assembly operation. Out of all the variables identified, dependant and independent variables of the axle

Manufacturing system are identified. The nos. of variables involved were large so they are reduced using dimensional analysis into few dimensionless pi terms. Buckingham pi theorem is used to establish dimensional equations to exhibit relationships between dependent terms and independent terms. A mathematical relationship is established between output parameters and input. The mathematical relationship exhibit that which input variables is to be maximized or minimized to optimize output variables. Once model is formulated it can be optimized using the optimization technique. Sensitivity analysis is a tool which can be used to find out the effect of input one parameter over the other. The model will be useful for an entrepreneur of an industry to select optimized inputs so as to get targeted responses.

Keywords— FDBM; filament winding; Dimensional analysis, mathematical model.

I. OVERVIEW OF FILAMENT WINDING

Filament winding is a technique used for the manufacture of surfaces of revolution such as pipes, tubes, cylinders, and spheres and is used frequently for the construction of large tanks and pipe work for the chemical industry. High-speed precise lay-down of continuous reinforcement in pre-described patterns is the basis of the filament-winding method. In a filament winding process, a band of continuous resin impregnated rovings or monofilaments is wrapped around a rotating mandrel and then cured either at room temperature or in an oven to produce the final product. The technique offers high speed and precise method for placing many composite layers. The reinforcements may be wrapped in adjacent bands that are stepped the width of the band and which eventually cover the entire mandrel surface. The technique has the capacity to vary the winding tension, wind angle, and resin content in each layer of reinforcement until the desired thickness and resin content of the composite are obtained. The winding angle used for construction of pipes or tanks depends on the strength-performance requirements and may vary from longitudinal through helical to circumferential,as shown. Often combinations of patterns are used. The mandrel can be cylindrical, round or any shape that does not have re-entrant curvature. Among the applications of filament winding are cylindrical and spherical pressure vessels, pipe lines, oxygen & other gas cylinders, rocket motor casings, helicopter blades, large underground storage tanks (for gasoline, oil, salts, acids, alkalies, water etc.). The process is not limited to axis-symmetric structures: prismatic shapes and more complex parts such as tee-joints, elbows may be wound on machines equipped with the appropriate number of degrees of freedom. Modern winding machines are numerically controlled with higher degrees of freedom for laying exact number of layers of reinforcement. Mechanical strength of the filament wound parts not only depends on composition of component material but also on process parameters like winding angle, fibre tension, resin chemistry and curing cycle

1.1.1 Design model

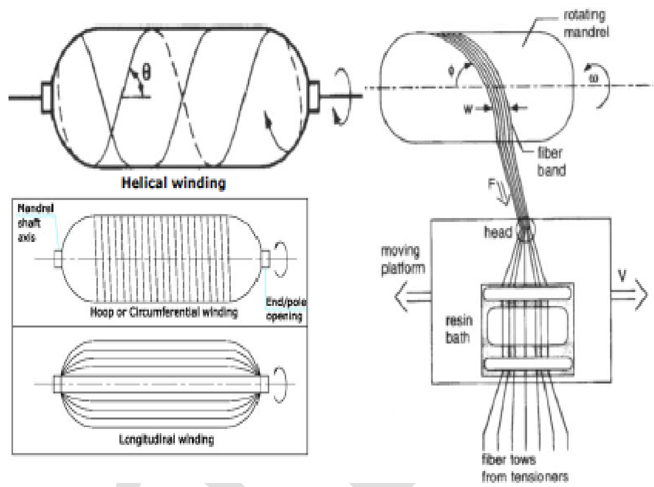
1.1.2 Process of filament winding

A winding operation is the basic fabrication technique for forming load-bearing structural elements made of polymer matrix-based fibrous composites, which have the shapes of bodies of revolution. A semifabricated product (uncured perform of previously impregnated filaments, strands, tapes and fabrics is wound layer by layer with controlled tension onto the mandrel or previous layers. By varying the angle of filament or tape placement, it is possible to control the reinforcement fiber angles within the same layer and through the thickness of the composite wall. During winding, fiber tension generates pressure between layers of uncured composite; this pressure influences the compaction and void content of the article and contributes to more complete utilization of the strength and stiffness of the reinforcing fibers. If the contact pressure is insufficient for compaction of the material, additional layer-by-layer compaction of asemi fabricated product must be employed. The wound article must be converted by chemical and/or thermal means to the finished article. With heat treatment, the usual method, the temperature can be constant or can vary with time. The mandrel defines the internal shape of the article. It is removed after curing if the mandrel is not an element of the structure.

Filament winding is a natural way to combine two-dimensional reinforcement and, with additional processes and devices, three- dimensional reinforcement. Advanced processes, combining filament winding and braiding, allow fabrication of spatially sewn structures.

The most important groups of wound articles are: thin-walled shells (their thickness is negligible compared to their radius)

There are three basic types of reinforcement configurations: circumferential, helical and polar. There are up to six degrees of freedom between the mandrel and the wind eye in typical advanced winding machines today and more motions are possible. Wind eyes can have three additional degrees of freedom (three rotational motions). The combination of several motions may allow more effective or rapid reinforcement placement on a complex surface.



Circumferential or hoop winding

The wind eye is stationary, except for travel along the length of the mandrel at a bandwidth per revolution and the mandrel together with the article rotates about one axis, i.e. for winding of rings, discs, profiled rings and discs (the ultimate case of profiling is the winding through an opening), short pipes, cones and other bodies of revolution. During circumferential winding, the shape of a cross section is decided either by the shape of the mandrel or by localized inserts, or by varying the bandwidth additional hoop layers. Some large and small-scale articles have been fabricated by rotating the wind eye about the stationary mandrel. Circular rings, ellipses, ovals and other shapes can be fabricated by a circumferential winding technique. The wind eye reciprocates parallel to the axis of the rotating mandrel and the article and is the most common technique used for tubular structures. By controlling the ratio of rotational and translational speeds, it is possible to control the wind angles of the reinforcement. Three other techniques can be used: one or more wind eyes are stationary, while the mandrel rotates and translates, the wind eye rotates around the translating mandrel, i.e. winding with a stationary whirling arm type winder which is one of the widely used methods of continuous fabrication of pipe; a wind eye rotates round a stationary mandrel and executes a translational motion along its axis. Winding with a whirling arm type winder is a popular method of insulating metallic pipelines. Circumferential winding is a particular case of helical winding with a wind angle of close to 90" (related to the band- width and the mandrel diameter).

Polar winding

This type of winding combines several different winding processes. It has the same combination of motions as helical winding, but the shortest axis is the axis of rotation. This technique combines two rotational motions. During simultaneous rotation of the mandrelaround its axis and the wind eye around an axis nearly perpendicular to it, a race-trackpattern is generated

This process enables the fabrication of vessels with different sized polar openings or closed ends. There are a number of alternative techniques. First, the wind eye executes a rotational motion in two planes. It is a very complex technique and is used only for unique articles. Second, the rotational motion of the mandrel is in two planes sometimes supplemented by a reciprocating motion of a wind eye or turning of its head.

there is a group involving three motions, two of which are rotational in two planes and one is translational. To this group belong, for example, a race-track type of winding, where a wind eye executes a motion along a closed but not circular trajectory. The trajectory shape affects the variation of the winding angle over the surface of the article. Pendulum winding is analogous to lathe winding, but instead of translation motion of a wind eye, there is a reciprocating motion along a curvilinear trajectory. One version of winding with a whirling arm-type winder is when a wind eye rotates and moves along some curvilinear trajectory. Fourthly, there is a group involving two rotational motions executed alternately (a planar-polar winding). Applications of this method include chord winding of composite flywheels.

Dimension Analysis of Filament winding process

Table 1. Dependent and Independent variable **For Filament winding Operation**

Dependent Variable

π	**Variables**	**Symbol**	**Unit**	**$M^0L^0T^0$**	**Dependant/ Independent**	**Variable/Constant**
01	DENSITY OF CY VESSEL	ρv	N/mm^3	$ML^{-3}T^0$	Dependent	Response Variable
02	Ultimate Tensile Strength of Cy. Vessel	бsh	N/mm^3	$ML\text{-}^{1}T^{-3}$	Dependent	Response Variable
03	cycle time Component Processing	tp	second	$M^0L^0T\text{-}^{1}$	Dependent	Response Variable
04	Fibre volume ratio 60%	fv	%	$M^0L^0T^0$	Dependent	Response Variable
05	Weight of shell	wsh	kgf	ML^0T^0	Dependent	Response Variable
1	DENSITY OF ACCELERATOR	ρ_{ac}	N/mm^3	$ML^{-3}T^0$	Independent	Variable
2	DENSITY OF ARALDITE	ρ_{ar}	N/mm^3	$ML^{-3}T^0$	Independent	Variable
3	DENSITY OF HARDENER	ρ_{hr}	N/mm^3	$ML^{-3}T^0$	Independent	Variable
4	DENSITY OF PLASTICIZER	ρ_{pl}	N/mm^3	$ML^{-3}T^0$	Independent	Variable
5	Specific Gravity of Glass Fibre	ρ_g	N/m^3	$ML^{-3}T^0$	Independent	Variable
6	Acceleration Due to gravity	g	m/s^2	$M^0L^{-1}T^{-2}$	Independent	Variable
7	Major Dia of vessel	D_s	**mm**	$M^0L^1T^0$	Independent	Variable
8	Viscosity of HARDENER	μ_{hr}	$N\cdot s/m^2$	$ML^{-1}T^{-1}$	Independent	Variable
9	Viscosity of PLASTICIZER	μ_{pl}	$N\cdot s/m^2$	$ML^{-1}T^{-1}$	Independent	Variable
10	Viscosity of	μ_{ac}	$N\cdot s/m^2$	$ML^{-1}T^{-1}$	Independent	Variable

	ACCELERATOR					
11	Viscosity of ARALDITE	μ_{ar}	$N{\cdot}s/m^2$	$ML^{-1}T^{-1}$	Independent	Variable
12	modulus of elasticity of glass fibre	E_g	N/mm^2	$ML^{-1}T^{-2}$	Independent	Variable
13	Tensile Stress of Glass Fibre	$Б_g$	N/mm^2	$ML^{-1}T^{-2}$	Independent	Variable
14	Pressure testing	P_t	N/mm^2	$ML^{-1}T^{-2}$	Independent	Variable
15	Carriage Speed	**Vs**	mm/s	$M^0L^1T^{-1}$	Independent	Variable
16	Carriage Feed	f_{ca}	**mm/min**	$M^0L^1T^{-1}$	Independent	Variable
17	Rotating Mandrel Speed	ω_m	**ω=2πN/60**	$M^0L^0T^{-1}$	Independent	Variable
18	Minor Dia of vessel	d_{sh}	**mm**	$M^0L^1T^0$	Independent	Variable
19	length of vessel	L_s	**mm**	$M^0L^1T^0$	Independent	Variable
20	Thickness of Glass Fibre	t_f	**mm**	$M^0L^1T^0$	Independent	Variable
21	length of Mandrel	L_m	**mm**	$M^0L^1T^0$	Independent	Variable
22	CONTENT OF ACCELERATOR	W_{ac}	**N**	$M^1L^0T^0$	Independent	Variable
23	CONTENT OF ARALDITE	W_{ar}	**N**	$M^1L^0T^0$	Independent	Variable
24	CONTENTOF HARDENER	W_{hr}	**N**	$M^1L^0T^0$	Independent	Variable
25	CONTENT OF PLASTICIZER	W_{pl}	**N**	$M^1L^0T^0$	Independent	Variable
26	TEX OF GLASS FIBRE	T_x	**N/km**	$ML^{-1}T^0$	Independent	Variable
27	Nos. of Layers/ Roving	N_{ro}	**nos.**	$M^0L^0T^{-0}$	Independent	Variable
28	Temperature of Curing Oven	t_C	$\mathbf{0^0C}$	$M^0L^0T^{-0}$	Independent	Variable
29	Angle of Roving	$Ø_{rov}$	**Φc**	$M^0L^0T^{-0}$	Independent	Variable

For Filament winding Operation:

$$\Pi_{01} = F(\Pi_1\Pi_2\Pi_3 \ldots\ldots\ldots\ldots\ldots \Pi_{29})$$

ρ_v =f(ρ_v, $б_{sh}$, t_pf_v, w_{sh} ,ρ_{ac}, ρ_{ar}, ρ_{hr}, ρ_{pl}, μ_{hr}, μ_{pl}, μ_{ac}, μ_{ar}, E_g, $Б_g$, P_t, V_s, f_{ca}, ω_m, d_{sh}, L_s, t_f, L_m, W_{ac}, W_{ar}, W_{hr}, W_{pl}, t_x, N_{ro}, t_C, Ørov,Nro,wsh, fv) ….(Equn. 4.1)

Consider repeating variables as (ρ_g), (g) & (D_s)

No. of actual variables=26

No. of repeating variables=3

Therefore No. of Π terms=n-m=26-3=23

$\Pi_1=(\rho_g)^{a1}(g)^{b1}(D_s)^{c1}(\rho_{ac})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)^{a1}(M^0L^1T^{-2})^{b1}(M^0L^1T^0)^{c1}(M^1L^{-3}T^0)$

For ‘M’	For ‘L’	For ‘T’
M→0=a_1+1=0 a_1=-1	L→0=-3a1+b1+c1-3 -3(-1)+(0)+c_1=3 c_1 = 0	T→ 0=-2b_1 b_1=-0

$\Pi_1=(\rho_g)^a{}_1(g)^b{}_1(D_s)^c{}_1(\rho_{ac})$

$\Pi_1=(\rho_g)^{-1}(g)^0(D_s)^0(\rho_{ac})$

DENSITY OF ACCELERATOR

$$\Pi_1 = \frac{\rho_{ac}}{\rho_g}$$

Similarly

DENSITY OF ARALDITE

$$\Pi_2 = \frac{\rho_{ar}}{\rho_g}$$

DENSITY OF HARDENER

$$\Pi_3 = \frac{\rho_{hr}}{\rho_g}$$

DENSITY OF PLASTICIZER

$$\Pi_4 = \frac{\rho_{pl}}{\rho_g}$$

$\Pi_5=(\rho_g)^{a}{}_{5}(g)^{b}{}_{5}(D_s)^{c}{}_{5}(\mu_{hr})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)^{a}{}_{5}(M^0L^1T^{-2})^{b}{}_{5}(M^0L^1T^0)^{c}{}_{5}(M^1L^{-1}T^{-1})$

For 'M'	For 'L'	For 'T'
$M \rightarrow 0= {}^{a}{}_{5}+1=0$	$L \rightarrow 0=-3a_5+b_5+c_5-1$	$T \rightarrow 0=-2b_5$
${}^{a}{}_{5}=-1$	C_5= -njh3/2	$B_5=-0$

$\Pi_5=(\rho_g)^{a}{}_{5}(g)^{b}{}_{1}(D_s)^{c}{}_{1}(\mu_{hr})$

$\Pi_5=(\rho_g)^{-1}(g)^{0}(D_s)^{-3/2}(\mu_{hr})$

VISCOSITY OF HARDENER

$$\Pi_5 = \frac{\mu_{hr}}{\rho_g Ds^{3/2}\sqrt{g}}$$

Similarly

VISCOSITY OF PLASTICIZER

$$\Pi_6 = \frac{\mu_{pl}}{\rho_g Ds^{3/2}\sqrt{g}}$$

VISCOSITY OF ACCELERATOR

$$\Pi_7 = \frac{\mu_{ac}}{\rho_g D s^{3/2}\sqrt{g}}$$

VISCOSITY OF ARALDITE

$$\Pi_8 = \frac{\mu_{ar}}{\rho_g D s^{3/2}\sqrt{g}}$$

$\Pi_9=(\rho_g)^{a}{}_{9}(g)^{b}{}_{9}(D_s)^{c}{}_{9}(E_g)$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\ {}^{a}{}_{9}\ (M^0L^1T^{-2})\ {}^{b}{}_{9}(M^0L^1T^0)\ {}^{c}{}_{9}(ML^{-1}T^{-2})$

For 'M'	For 'L'	For 'T'
M→0= ${}^{a}{}_{9}$+1=0	L→0=-3a$_9$+b$_9$+c$_9$-1	T→ 0=-2b$_9$-2
${}^{a}{}_{9}$=-1	C$_9$= -1	B$_9$=-1

$\Pi_9=(\rho_g)^{a}{}_{5}\ (g)^{b}{}_{1}(D_s)^{c}{}_{1}(E_g)$

$\Pi_9=(\rho_g)^{-1}(g)^{-1}(D_s)^{-1}(E_g)$

MODULUS OF ELASTICITY OF GLASS FIBER

$$\Pi_9=\frac{E_{sh}}{gDs\rho_g}$$

Similarly

TENSILE STRESS OF GLASS FIBRE

$$\Pi_{10}=\frac{6fi}{gDs\rho_g}$$

PRESSURE TESTING

$$\Pi_{11}=\frac{Pt}{gDs\rho_g}$$

$\Pi_{12}=(\rho_g)^{a}{}_{12}(g)^{b}{}_{12}(D_s)^{c}{}_{12}(\mathbf{Vs})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\ {}^{a}{}_{12}\ (M^0L^1T^{-2})\ {}^{b}{}_{12}(M^0L^1T^0)\ {}^{c}{}_{12}(M^0L^1T^{-1})$

For 'M'	For 'L'	For 'T'
M→0=0	L→0=-3a$_{12}$+b$_{12}$+c$_{12}$+1	T→ 0=-2b$_{12}$-1
${}^{a}{}_{12}$=0	b$_{12}$+c$_{12=}$ -1, C$_{12}$= -1/2	B$_{12}$=-1/2

$\Pi_{12}=(\rho_g)^{a}{}_{12}\ (g)^{b}{}_{12}(D_{12})^{c}{}_{12}(\mathbf{Vs})$

$\Pi_{12}=(\rho_g)^{0}(g)^{-1/2}(D_s)^{-1/2}(\mathbf{Vs})$

CARRIAGE SPEED

$$\Pi_{12}=\frac{V_s}{\sqrt{gD_s}}$$

Similarly

CARRIAGE FEED

$$\Pi_{13}=\frac{F_{ca}}{\sqrt{gD_s}}$$

$\Pi_{14}=(\rho_g)^{a}{}_{14}(g)^{b}{}_{14}(D_s)^{c}{}_{14}(\boldsymbol{\omega_m})$

$(M)^0(L)^0(T)^0=(M^1L^{-3}T^0)^{a}{}_{14}\,(M^0L^1T^{-2})^{b}{}_{14}(M^0L^1T^0)^{c}{}_{14}(M^0L^0T^{-1})$

For 'M'	For 'L'	For 'T'
$M\rightarrow 0=0$	$L\rightarrow 0=b_{14}+c_{14}$	$T\rightarrow 0=-2b_{14}-1$
${}^{a}{}_{14}=0$	$b_{14}+c_{14=}-1$	$B_{14}=-1/2$
	$C_{14}=1/2$	

$\Pi_{14}=(\rho_g)^{a}{}_{14}\,(g)^{b}{}_{14}(D_s)^{c}{}_{14}(\boldsymbol{\omega_m})$

$\Pi_{14}=(\rho_g)^0(g)^{-1/2}(D_s)^{1/2}(\boldsymbol{\omega_m})$

ROTATING MANDREL SPEED

$$\Pi_{14}=\sqrt{\frac{D_s}{g}}\omega_m$$

$\Pi_{15}=(\rho_g)^{a}{}_{15}(g)^{b}{}_{15}(D_s)^{c}{}_{15}(\mathbf{d_s})$

$(M)^0(L)^0(T)^0=(M^1L^{-3}T^0)^{a}{}_{15}\,(M^0L^1T^{-2})^{b}{}_{15}(M^0L^1T^0)^{c}{}_{15}(M^0L^1T^0)$

For 'M'	For 'L'	For 'T'
$M\rightarrow 1a_{15}=0$	$L\rightarrow 0=-3a_{15}+b_{15}+c_{15}+1$	$T\rightarrow 0=-2b_{15}$
${}^{a}{}_{15}=0$	$c_{15=}-1C_{15}=-1$	$B_{15}=0$

$\Pi_{15}=(\rho_g)^{a}{}_{15}\,(g)^{b}{}_{15}(D_s)^{c}{}_{15}(\mathbf{d_s})$

$\Pi_{15}=(\rho_g)^0(g)^0(D_s)^{-1}(\mathbf{d_s})$

MINOR DIA OF VESSEL

$$\Pi_{15}=\frac{d_s}{D_s}$$

Similarly

LENGTH OF VESSEL

$$\Pi_{16}=\frac{L_{sh}}{D_s}$$

THICKNESS OF GLASS FIBRE

$$\Pi_{17} = \frac{t_{fib}}{D_s}$$

LENGTH OF MANDREL

$$\Pi_{18} = \frac{L_{mand}}{D_s}$$

$\Pi_{19}=(\rho_g)^{a}{}_{19}(g)^{b}{}_{19}(D_s)^{c}{}_{19}(W_{ac})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\,^{a}{}_{19}\,(M^0L^1T^{-2})\,^{b}{}_{19}(M^0L^1T^0)\,^{c}{}_{15}(M^1L^0T^0)$

For 'M'	For 'L'	For 'T'
$M\rightarrow a_{19}+1=0$	$L\rightarrow 0=-3a_{19}+b_{19}+c_{15}+1$	$T\rightarrow 0=-2b_{19}$
$^{a}{}_{19}=-1$	$3+c_{19=}\,0C_{19}=3$	$B_{15}=0$

$\Pi_{15}=(\rho_g)^{a}{}_{19}\,(g)^{b}{}_{19}(D_s)^{c}{}_{19}(W_{ac})$

$\Pi_{15}=(\rho_g)^{-1}(g)^0(D_s)^3(W_{ac})$

CONTENT OF ACCELERATOR

$$\Pi_{19} = \frac{W_{acc}}{\rho_g (Ds)^{3/2}}.$$

CONTENT OF ARALDITE

$$\Pi_{20} = \frac{W_{ara}}{\rho_g (Ds)^{3/2}}.$$

CONTENT OF HARDENER

$$\Pi_{21} = \frac{W_{har}}{\rho_g (Ds)^{3/2}}.$$

CONTENT OF PLASTICIZER

$$\Pi_{22} = \frac{W_{pla}}{\rho_g (Ds)^{3/2}}.$$

$\Pi_{23}=(\rho_g)^{a}{}_{23}(g)^{b}{}_{23}(D_s)^{c}{}_{23}(\mathbf{T_x})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\,^{a}{}_{23}\,(M^0L^1T^{-2})\,^{b}{}_{23}(M^0L^1T^0)\,^{c}{}_{23}(\mathbf{ML}^{-1}T^0)$

For 'M'	For 'L'	For 'T'
$M\rightarrow a_{23}+1=0$	$L\rightarrow 0=-3a_{23}-b_{23}+c_{23}-1$	$T\rightarrow 0=-2b_{23}$
$^{a}{}_{23}=-1$	$C_{23}=-2$	$B_{23}=0$

$\Pi_{23}=(\rho_g)^{a}{}_{23}\,(g)^{b}{}_{23}(D_s)^{c}{}_{23}(\mathbf{T_x})$

$\Pi_{23}=(\rho_g)^{-1}(g)^0(D_s)^{-2}(\mathbf{T_x})$

TEX OF GLASS FIBRE

$\Pi_{23} = \frac{T_x}{\rho_g (Ds)^2}$

ρ_v =f(ρ_v, $б_{sh}$, $t_p f_v$,……………………………………………23)….(Equn. 4.1)

ρ_v =f(ρ_v, $б_{sh}$, $t_p f_v$, w_{sh} ,ρ_{ac}, ρ_{ar}, ρ_{hr}, ρ_{pl}, μ_{hr}, μ_{pl}, μ_{ac}, μ_{ar}, E_g, $Б_g$, P_t, V_s, f_{ca}, ω_m, d_{sh}, L_s, t_f, L_m, W_{ac}, W_{ar}, W_{hr}, W_{pl}, t_x, N_{ro}, t_C, $Ø_{rov}$Nro, wsh, fv) ….(Equn. 4.2)

ρ_v =f($\frac{\rho_{ac}}{\rho_g}$, $\frac{\rho_{ar}}{\rho_g}$, $\frac{\rho_{hr}}{\rho_g}$, $\frac{\rho_{pl}}{\rho_g}$, $\frac{\mu_{hr}}{\rho_g Ds^{3/2}\sqrt{g}}$, $\frac{\mu_{pl}}{\rho_g Ds^{3/2}\sqrt{g}}$, $\frac{\mu_{ac}}{\rho_g Ds^{3/2}\sqrt{g}}$, $\frac{\mu_{ar}}{\rho_g Ds^{3/2}\sqrt{g}}$, $\frac{d_s}{D_s}$, $\frac{L_{sh}}{D_s}$, $\frac{t_{fib}}{D_s}$, $\frac{L_{mand}}{D_s}$, $\frac{W_{acc}}{\rho_g (Ds)^{3/2}}$, $\frac{W_{ara}}{\rho_g (Ds)^{3/2}}$, $\frac{W_{har}}{\rho_g (Ds)^{3/2}}$, $\frac{W_{pla}}{\rho_g (Ds)^{3/2}}$, $\frac{E_{sh}}{gDs\rho_g}$, $\frac{бfi}{gDs\rho_g}$, $\frac{psh}{gDs\rho_g}$, $\frac{V_s}{\sqrt{gD_s}}$, $\frac{F_{ca}}{\sqrt{gD_s}}$, $\sqrt{\frac{D_s}{g}}\omega_m$, $\frac{T_x}{\rho_g (Ds)^2}$,Nro, wsh, fv) ….(Equn. 4.3)

Reduction of Pi Terms

$\pi_1 = \{\frac{\rho_{ac}}{\rho_g} \frac{\rho_{ar}}{\rho_g} \frac{\rho_{hr}}{\rho_g} \frac{\rho_{pl}}{\rho_g}\}$

$\pi_1 = \{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\}$………- **Related to Density of ingredient/mixture**

$\pi_2 = \{\frac{\mu_{hr}}{\rho_g Ds^{3/2}\sqrt{g}} \frac{\mu_{pl}}{\rho_g Ds^{3/2}\sqrt{g}} \frac{\mu_{ac}}{\rho_g Ds^{3/2}\sqrt{g}} \frac{\mu_{ar}}{\rho_g Ds^{3/2}\sqrt{g}}\}$

$\pi_2 = \{\frac{\mu_{hr,}\mu_{pl,}\mu_{ac,}\mu_{pl}}{g^2 \rho_g{}^4 D_s{}^6}\}$-…….**Related to Viscocity of ingredient/mixture**

$\pi_3 = \{\frac{W_{acc}}{\rho_g (Ds)^{3/2}}, \frac{W_{ara}}{\rho_g (Ds)^{3/2}}, \frac{W_{har}}{\rho_g (Ds)^{3/2}}, \frac{W_{pla}}{\rho_g (Ds)^{3/2}}.\}$

$\pi_3 = \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4 D_s{}^{12}}\}$-…………….**Related to weight of ingredient/mixture**

$\pi_4 = \{\frac{E_{sh}}{gDs\rho_g} \frac{бfi}{gDs\rho_g} \frac{psh}{gDs\rho_g}\}$

$\pi_4 = \{\frac{Psh,\ E_{sh},\ \sigma fi}{g^3 \rho_g{}^3 D_s{}^3}\}$-……………**Related to Viscosity of ingredient/mixture**

$\pi_5 = \{\frac{V_s}{\sqrt{gD_s}} \frac{F_{ca}}{\sqrt{gD_s}}\}$

$\pi_5 = \{\frac{V_s}{g} \frac{F_{ca}}{D_s}\}$-………………………**Related to velocity of carriage**

$\pi_6 = \{\sqrt{\frac{D_s}{g}}\omega_m\}$ ……………………**Related to rotating mandrel speed**

$\pi_7 = \{\frac{T_x}{\rho_g (Ds)^2}\}$……………………………**Related to tex of glass fiber**

$\pi_8 = \{\frac{d_s}{D_s} \frac{L_{sh}}{D_s} \frac{t_{fib}}{D_s} \frac{L_{mand}}{D_s}\}$

$\pi_8 = \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g{}^3 D_s{}^3}\}$-……… …….**Related to Geometric parameter**

$\pi_9 = \{Nro,\ wsh,\ fv\}$…………………**Related to Viscocity of ingredient/mixture**

$\rho_v = f(\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\}, \{\frac{\mu_{hr}, \mu_{pl}, \mu_{ac}, \mu_{pl}}{g^2 \rho_g{}^4 D_s{}^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4 D_s{}^{12}}\}, \{\frac{Psh,\ E_{sh},\ \sigma fi}{g^3 \rho_g{}^3 D_s{}^3}\}, \{\frac{V_s}{g} \frac{F_{ca}}{D_s}\}, \{\sqrt{\frac{D_s}{g}}\omega_m\},$
$\{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g{}^3 D_s{}^3}\}, \{Nro,\ wsh,\ fv\}$ ….(Equn. 4.1)

FOR DEPENDANT Pi TERMS :

i) **For Density of cylindrical pressure vessel (ρ_{cv})**

$\Pi_{01} = (\rho_g)^{a}{}_{01}(g)^{b}{}_{01}(D_s)^{c}{}_{01}(\rho_{cv})$

$(M)^0(L)^0(T)^0 = (M^1L^{-3}T^0)^{a}{}_{01}(M^0L^1T^{-2})^{b}{}_{01}(M^0L^1T^0)^{c}{}_{01}(M^1L^{-3}T^0)$

For 'M'	For 'L'	For 'T'
$M \rightarrow 0 = a_{01}+1=0$	$L \rightarrow 0 = -3a_{01}+b_{01}+c_{01}-3$	$T \rightarrow 0 = -2b_{01}$
$A_{01} = -1$	$-3(-1)+(0)+c_{01}=3$	$B_{01} = -0$
	$C_{01} = 0$	

$\Pi_{01} = (\rho_g)^{a}{}_{01}(g)^{b}{}_{01}(D_s)^{c}{}_{01}(\rho_{cv})$

$\Pi_{01} = (\rho_g)^{-1}(g)^0(D_s)^0(\rho_{cv})$

DENSITY OF **cylindrical pressure vessel** (ρ_{cv})

$$\Pi_{01} = \frac{\rho_{cv}}{\rho_g}$$

ii) For UTS of cylindrical pressure vessel (б_{cv})

$\Pi_{02}=(\rho_g)^{a}{}_{02}(g)^{b}{}_{02}(D_s)^{c}{}_{02}(\text{б}_{cv})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\,^{a}{}_{02}\,(M^0L^1T^{-2})\,^{b}{}_{02}(M^0L^1T^0)\,^{c}{}_{02}(ML^{-1}T^{-2})$

For 'M'	For 'L'	For 'T'
M→0= $^{a}{}_{02}$+1=0	L→0=-3a_{02}+b_{02}+c_{02}-1	T→ 0=-2b_{02}-2
$^{a}{}_{02}$=-1	C_{02}= -1	B_{02}=-1

$\Pi_{02}=(\rho_g)\,^{a}{}_{02}\,(g)^{b}{}_{02}(D_s)^{c}{}_{02}(\text{б}_{cv}))$

$\Pi_{02}=(\rho_g)^{-1}(g)^{-1}(D_s)^{-1}(\text{б}_{cv}))$

UTS of cylindrical pressure vessel (б_{cv})

$$\Pi_{02} = \frac{E_{cv}}{gDs\rho_g}$$

iii) For cycle time for component processing (t_{cp})

$\Pi_{03}=(\rho_g)^{a}{}_{03}(g)^{b}{}_{03}(D_s)^{c}{}_{03}(\mathbf{t_{cp}})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\,^{a}{}_{03}\,(M^0L^1T^{-2})\,^{b}{}_{03}(M^0L^1T^0)\,^{c}{}_{03}(M^0L^0T^1)$

For 'M'	For 'L'	For 'T'
M→0= $^{a}{}_{03}$=0	L→0=-3a_{03}+b_{03}+c_{03}-1	T→ 0=-2b_{03}+1
$^{a}{}_{03}$=0	C_{03}= -1/2	B_{03}=-1/2

$\Pi_{02}=(\rho_g)\,^{a}{}_{03}\,(g)^{b}{}_{03}(D_s)^{c}{}_{03}(\mathbf{t_{cp}}))$

$\Pi_{02}=(\rho_g)^{-1}(g)^{1/2}(D_s)^{-1/2}(\mathbf{t_{cp}})$

cycle time for component processing (t_{cp})

$$\Pi_{03} = \frac{\sqrt{g}\,.\mathbf{tcp}}{\sqrt{D_s}}$$

iv) For cycle time for component processing (t_{cp})

$\Pi_{04}=f_{vr}$

v) For Weight of Cy. Vessel (Wcv)

$\Pi_{05}=(\rho_g)^{a}{}_{05}(g)^{b}{}_{05}(D_s)^{c}{}_{05}(\mathbf{W_{cv}})$

$(M)^0(L)^0(T)^0= (M^1L^{-3}T^0)\,^{a}{}_{05}\,(M^0L^1T^{-2})\,^{b}{}_{05}(M^0L^1T^0)\,^{c}{}_{05}(M^1L^0T^0)$

For 'M'	For 'L'	For 'T'
M→a_{05}+1=0	L→0=-3a_{05}+b_{05}+c_{05}+1	T→ 0=-2b_{19}
$^{a}{}_{05}$=-1	3+$c_{05=}$ 0 C_{05}=3	B_{05}=0

$\Pi_{15}=(\rho_g)^{a}{}_{19}\,(g)^{b}{}_{19}(D_s)^{c}{}_{19}(\mathbf{W_{cv}})$

$\Pi_{15}=(\rho_g)^{-1}(g)^{0}(D_s)^{3}(\mathbf{W_{cv}})$

For Weight of Cy. Vessel (Wcv)

$$\Pi_{05}=\frac{W_{cv}}{\rho_g(Ds)^{3/2}}$$

Therefore the final equations for dependant pi terms are as follows:

For Density of cylindrical pressure vessel (ρ_{cv})

$$\Pi_{01}=f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g{}^4D_s{}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4D_s{}^{12}}\right\},\left\{\frac{Psh,E_{sh,}\text{б}fi}{g^3\rho_g{}^3D_s{}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{(d_sl_{sh}t_{fib}l_{ma}}{g^3\rho_g{}^3D_s{}^3}\right\},\{Nro, wsh, fv\}\right)\ \text{....(Equn.)}$$

$$\frac{\rho_{cv}}{\rho_g}=f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g{}^4D_s{}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4D_s{}^{12}}\right\},\left\{\frac{Psh,E_{sh,}\text{б}fi}{g^3\rho_g{}^3D_s{}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{(d_sl_{sh}t_{fib}l_{ma}}{g^3\rho_g{}^3D_s{}^3}\right\},\{Nro, wsh, fv\}\right)\ \text{....(Equn.)}$$

$$\rho_{cv}=K\rho_g f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g{}^4D_s{}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4D_s{}^{12}}\right\},\left\{\frac{Psh,E_{sh,}\text{б}fi}{g^3\rho_g{}^3D_s{}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{(d_sl_{sh}t_{fib}l_{ma}}{g^3\rho_g{}^3D_s{}^3}\right\},\{Nro, wsh, fv\}\right)$$

For UTS of cylindrical pressure vessel (б_{cv})

$$\Pi_{02}=f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g{}^4D_s{}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4D_s{}^{12}}\right\},\left\{\frac{Psh,E_{sh,}\text{б}fi}{g^3\rho_g{}^3D_s{}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{(d_sl_{sh}t_{fib}l_{ma}}{g^3\rho_g{}^3D_s{}^3}\right\},\{Nro, wsh, fv\}\right)\ \text{....(Equn. 4.1)}$$

$$\frac{E_{cv}}{gDs\rho_g}=f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g{}^4D_s{}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4D_s{}^{12}}\right\},\left\{\frac{Psh,E_{sh,}\text{б}fi}{g^3\rho_g{}^3D_s{}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{(d_sl_{sh}t_{fib}l_{ma}}{g^3\rho_g{}^3D_s{}^3}\right\},\{Nro, wsh, fv\}\right)$$

$$E_{cv}=K(gDs\rho_g)\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g{}^4D_s{}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g{}^4D_s{}^{12}}\right\},\left\{\frac{Psh,E_{sh,}\text{б}fi}{g^3\rho_g{}^3D_s{}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\right.$$

$\{\sqrt{\frac{D_s}{g}}\omega_m\}, \{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$

For cycle time for component processing (t_{cp})

$\Pi_{03} = f(\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_g)^4}\}, \{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g^4 D_s^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g^4 D_s^{12}}\}, \{\frac{Psh, E_{sh}, \sigma fi}{g^3\rho_g^3 D_s^3}\}, \{\frac{V_s}{g}\frac{F_{ca}}{D_s}\}, \{\sqrt{\frac{D_s}{g}}\omega_m\},$

$\{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$ ….(Equn. 4.1)

$\frac{\sqrt{g}.tcp}{\sqrt{D_s}} = f(\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\}, \{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g^4 D_s^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g^4 D_s^{12}}\}, \{\frac{Psh, E_{sh}, \sigma fi}{g^3\rho_g^3 D_s^3}\}, \{\frac{V_s}{g}\frac{F_{ca}}{D_s}\}, \{\sqrt{\frac{D_s}{g}}\omega_m\},$

$\{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$

$\sqrt{g}.\mathbf{tcp} = K \sqrt{D_s}(\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\}, \{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g^4 D_s^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g^4 D_s^{12}}\}, \{\frac{Psh, E_{sh}, \sigma fi}{g^3\rho_g^3 D_s^3}\}, \{\frac{V_s}{g}\frac{F_{ca}}{D_s}\},$

$\{\sqrt{\frac{D_s}{g}}\omega_m\}, \{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$

For cycle time for component processing (t_{cp})

$\Pi_{04} = f(\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_g)^4}\}, \{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g^4 D_s^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g^4 D_s^{12}}\}, \{\frac{Psh, E_{sh}, \sigma fi}{g^3\rho_g^3 D_s^3}\}, \{\frac{V_s}{g}\frac{F_{ca}}{D_s}\}, \{\sqrt{\frac{D_s}{g}}\omega_m\},$

$\{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$….(Equn. 4.1)

$f_{vr} = K (\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\}, \{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g^4 D_s^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g^4 D_s^{12}}\}, \{\frac{Psh, E_{sh}, \sigma fi}{g^3\rho_g^3 D_s^3}\}, \{\frac{V_s}{g}\frac{F_{ca}}{D_s}\}, \{\sqrt{\frac{D_s}{g}}\omega_m\},$

$\{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$

$f_{vr} = K (\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\}, \{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2\rho_g^4 D_s^6}\}, \{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{\rho_g^4 D_s^{12}}\}, \{\frac{Psh, E_{sh}, \sigma fi}{g^3\rho_g^3 D_s^3}\}, \{\frac{V_s}{g}\frac{F_{ca}}{D_s}\}, \{\sqrt{\frac{D_s}{g}}\omega_m\},$

$\{\frac{T_x}{\rho_g (Ds)^2}\}, \{\frac{(d_s l_{sh} t_{fib} l_{ma}}{g^3 \rho_g^3 D_s^3}\}, \{Nro, wsh, fv\})$

For Weight of Cy. Vessel (Wcv)

$$\Pi_{05} = f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2{\rho_g}^4{D_s}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{{\rho_g}^4{D_s}^{12}}\right\},\left\{\frac{Psh,\ E_{sh},\ \sigma fi}{g^3{\rho_g}^3{D_s}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{d_s l_{sh} t_{fib} l_{ma}}{g^3{\rho_g}^3{D_s}^3}\right\},\{Nro,\ wsh,\ fv\}\right) \quad \text{….(Equn. 4.1)}$$

$$\frac{W_{cv}}{\rho_g(Ds)^{3/2}} = f\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2{\rho_g}^4{D_s}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{{\rho_g}^4{D_s}^{12}}\right\},\left\{\frac{Psh,\ E_{sh},\ \sigma fi}{g^3{\rho_g}^3{D_s}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{d_s l_{sh} t_{fib} l_{ma}}{g^3{\rho_g}^3{D_s}^3}\right\},\{Nro,\ wsh,\ fv\}\right)$$

$$W_{cv} = K\ \left(\rho_g(Ds)^{3/2}\right)\left(\left\{\frac{\rho_{ac}\rho_{ar}\rho_{hr}\rho_{pl}}{(\rho_{ac})^4}\right\},\left\{\frac{\mu_{hr},\mu_{pl},\mu_{ac},\mu_{pl}}{g^2{\rho_g}^4{D_s}^6}\right\},\left\{\frac{W_{ac}W_{ar}W_{hr}W_{pl}}{{\rho_g}^4{D_s}^{12}}\right\},\left\{\frac{Psh,\ E_{sh},\ \sigma fi}{g^3{\rho_g}^3{D_s}^3}\right\},\left\{\frac{V_s}{g}\frac{F_{ca}}{D_s}\right\},\left\{\sqrt{\frac{D_s}{g}}\omega_m\right\},\left\{\frac{T_x}{\rho_g(Ds)^2}\right\},\left\{\frac{d_s l_{sh} t_{fib} l_{ma}}{g^3{\rho_g}^3{D_s}^3}\right\},\{Nro,\ wsh,\ fv\}\right)$$

DEPENDENT VARIABLES

Dependent Variables								
π_{01}	π_{001}	π_{02}	π_{002}	π_{03}	π_{003}	π_{04}	π_{05}	π_{005}
DENSITY OF VESSEL	$\frac{\rho_{cv}}{\rho_g}$	*Ultimate Tensile Strength of SHELL*	$\frac{E_{cv}}{gDs\rho_g}$	*cycle time*	$\frac{\sqrt{g}.tcp}{\sqrt{D_s}}$	*Fiber volume ratio 60%*	*Weight of shell*	$\frac{W_{cv}}{\rho_g(Ds)^{3/2}}$
ρ_{sh}		σ_{fib}		t_{comp}		fv_{shell}	w_{shell}	
1.9 ± 5% gm/cm^3		*210 N/mm^2*		*10-11 HRS*		*60±2%*	*6.260 Kg*	
Kg/m^3		*N/m^2*		*second*		*%*	*Kg*	
1805.000		210000000.000		36000.000		59.000	6.260	
1995.000		210000000.000		39600.000		61.000	5.634	
1805.000	736.434	210000000.000	40892362.959	36000.000	243731.515	59.000	5.635	470.498
1880.000	752.000	210000000.000	40072129.834	36018.000	268041.989	60.000	5.800	474.117
1810.000	680.451	210000000.000	37644177.199	36036.000	243617.595	61.000	6.100	467.990
1900.000	703.704	210000000.000	37069163.646	36054.000	243682.476	59.000	5.685	429.088
1990.000	783.465	210000000.000	39441072.671	36072.000	243918.210	60.000	5.634	453.295
1900.000	772.358	210000000.000	40723709.181	36090.000	244040.047	61.000	6.200	515.056

1950.000	*792.683*	*210000000.000*	*40742756.753*	*36108.000*	*244218.978*	*60.000*	*6.100*	*507.460*
1805.000	*731.955*	*210000000.000*	*40586675.524*	*36126.000*	*244169.597*	*60.000*	*6.085*	*502.860*
1880.000	*764.228*	*210000000.000*	*40666673.173*	*36144.000*	*244234.346*	*59.000*	*5.952*	*492.379*
1810.000	*680.451*	*210000000.000*	*37661776.159*	*36162.000*	*244527.396*	*61.000*	*5.756*	*442.218*
1900.000	*712.946*	*210000000.000*	*37608698.541*	*36180.000*	*244706.441*	*59.000*	*6.111*	*469.269*
1990.000	*765.385*	*210000000.000*	*38530894.071*	*36198.000*	*244771.071*	*60.000*	*6.252*	*491.409*
1900.000	*742.188*	*210000000.000*	*39151242.817*	*36216.000*	*244950.173*	*61.000*	*6.200*	*495.631*
1950.000	*764.107*	*210000000.000*	*39273973.986*	*36234.000*	*245072.038*	*60.000*	*5.960*	*477.939*
1800.000	*692.308*	*210000000.000*	*38530894.071*	*36252.000*	*245136.582*	*61.000*	*5.698*	*447.865*
1885.000	*708.647*	*210000000.000*	*37644177.199*	*36270.000*	*245201.110*	*59.000*	*5.985*	*459.168*
1845.000	*715.116*	*210000000.000*	*38793310.792*	*36288.000*	*245265.620*	*60.000*	*5.682*	*448.809*
1835.000	*764.583*	*210000000.000*	*41741801.910*	*36306.000*	*245502.094*	*61.000*	*5.687*	*484.250*
1855.000	*713.462*	*210000000.000*	*38530894.071*	*36324.000*	*245623.931*	*60.000*	*5.792*	*455.253*
1900.000	*730.769*	*210000000.000*	*38548916.004*	*36342.000*	*245803.233*	*60.000*	*6.120*	*481.709*
1925.000	*751.953*	*210000000.000*	*39096383.532*	*36360.000*	*245752.741*	*59.000*	*6.100*	*485.590*

INDEPENDENT VARIABLES

π_1	π_2	π_3	π_4	π_5	π_6	π_7	π_8	π_9	π_{10}
DENSITY OF ACCELERATOR	*DENSITY OF ARALDITE*	*DENSITY OF HARDENER*	*DENSITY OF PLASTICIZER*	*Viscocity of HARDENER*	*Viscocity of PLASTICIZER*	*Viscocity of ARALDITE*	*Viscocity of Accelerater*	*Tensile Stress of Glass Fibre*	*modulus of elasticity of glass fiber*
ρ_{acc}	ρ_{ar}	ρ_{hr}	ρ_{pl}	μ_{hr}	μ_{pl}	μ_{re}	μ_{ac}	σ_{fib}	E_{fib}
kg/m^3	kg/m^3	kg/m^3	kg/m^3	$N{\cdot}s/m^2$	$N{\cdot}s/m^2$	$N{\cdot}s/m^2$	$N{\cdot}s/m^2$	N/m^2	N/m^2
1.0-1.05 gm/cm^3	1.15-1.2 gm/cm^3	1.15-1.25 gm/cm^3	0.95-1.05 gm/cm^3	150-250 mPa s	50-110 mPa s	800-2000 mPa s	0.895-0.91 mPa s	488N/mm^2	**2.57 GPA**
Kg/m^3	**Kg/m^3**	**Kg/m^3**	**Kg/m^3**	$N{\cdot}s\ m^2$	$N{\cdot}s\ m^2$	$N{\cdot}s\ m^2$	$N{\cdot}s\ m^2$	N/m^2	N/m^2
1000.000	1150.000	1150.000	950.000	150000.000	50000.000	800000.000	895.000	0.488	2570000.000
1050.000	1200.000	1250.000	1050.000	250000.000	110000.000	2000000.000	910.000		2570000.000
1011.000	***1161.000***	***1156.000***	***966.000***	***150000.000***	***50000.000***	***800000.000***	***910.000***	***488000.000***	2570000.000
1050.000	***1162.000***	***1156.000***	***956.000***	***160000.000***	***60000.000***	***890000.000***	***895.000***	***488000.000***	2570000.000
1020.000	***1168.000***	***1236.000***	***986.000***	***185000.000***	***65000.000***	***1200000.000***	***910.000***	***488000.000***	2570000.000
1011.000	***1159.000***	***1256.000***	***1020.000***	***195000.000***	***56000.000***	***1800000.000***	***920.000***	***488000.000***	2570000.000
1013.000	***1159.000***	***1189.000***	***1005.000***	***200000.000***	***75000.000***	***1400000.000***	***910.000***	***488000.000***	2570000.000
1014.000	***1157.000***	***1196.000***	***1021.000***	***225000.000***	***100000.000***	***1500000.000***	***895.000***	***488000.000***	2570000.000
1036.000	***1185.000***	***1195.000***	***1034.000***	***190000.000***	***105000.000***	***1890000.000***	***910.000***	***488000.000***	2570000.000
1035.000	***1194.000***	***1156.000***	***1050.000***	***185000.000***	***90000.000***	***1850000.000***	***920.000***	***488000.000***	2570000.000
1025.000	***1159.000***	***1163.000***	***986.000***	***160000.000***	***80000.000***	***1482000.000***	***910.000***	***488000.000***	2570000.000
1045.000	***1189.000***	***1185.000***	***999.000***	***160000.000***	***75600.000***	***785000.000***	***910.000***	***488000.000***	2570000.000
1044.000	***1199.000***	***1156.000***	***985.000***	***185000.000***	***55000.000***	***987000.000***	***895.000***	***488000.000***	2570000.000
1028.000	***1192.000***	***1199.000***	***1005.000***	***175000.000***	***65400.000***	***1258000.000***	***910.000***	***488000.000***	2570000.000
1029.000	***1185.000***	***1200.000***	***1025.000***	***168000.000***	***56800.000***	***1654000.000***	***910.000***	***488000.000***	2570000.000
1021.000	***1179.000***	***1250.000***	***1025.000***	***220000.000***	***56500.000***	***1951000.000***	***910.000***	***488000.000***	2570000.000

INDEPENDENT VARIABLES

π_{11}	π_{13}	π_{14}	π_{15}	π_{16}	π_{17}	π_{18}	π_{19}	π_{20}	π_{22}
Pressure testing	*length of shell*	*Thickness of Glass Fibre*	*length of Mandrel*	*CONTENT OF ACCELERATOR*	*CONTENT OF ARALDITE*	*CONTENT OF HARDENER*	*CONTENTOF PLASTICIZER*	*Carriage Speed*	*Carriage Feed*
p_{shell}	L_{shell}	t_{fib}	L_{mand}	W_{acc}	W_{ara}	W_{har}	W_{pla}	s_{carr}	f_{carr}
N/m^2	*m*	*m*	*m*	*Kg*	*Kg*	*Kg*	*Kg*	*m/s*	*m/s*
30 Kg/cm^2	**895mm**	**0.65mm**	**1000mm**	**20 gm**	**2 Kg**	**2 Kg**	**200 gm**	**30.000**	**2.4mm/s**
N/m^2	**m**	**m**	**m**	**Kg**	**Kg**	**Kg**	**Kg**	**m/s**	**m/s**
2941995.000	0.895	0.000	1.000	0.200	2.000	2.000	0.200	30.000	**0.002**
294.000	0.895	0.000	1.000	0.200	2.000	2.000	0.200	24.000	**0.002**
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***
2940000.000	***0.895***	***0.650***	***1000.000***	**0.020**	**2.000**	**2.000**	***0.200***	***30.000***	***2400.000***

CONCLSION

It is seen that filament winding process/Manufacturing system for cylindrical pressure vesselare identified. The dependent and independent variables involved were large so they are reduced using dimensional analysis & pi terms evaluated. Buckingham pi theorem is used to establish dimensional equations to exhibit relationships between dependent terms and independent terms. A mathematical relationship is established between output parameters and input. The mathematical relationship exhibit that which input variables is to be maximized or minimized to optimize output variables. After model is formulated it mow possible for optimizing entire process.. The model will be useful for an composite industry/entrepreneur of an industry to select optimized inputs so as to get targeted responses.

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