

EFFECT OF NATURAL CONVECTION HEAD ON COASTDOWN TRANSIENTS FLOW TIME

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ABSTRACT

In this paper, it is attempted to use pump characteristics curve in order to estimate coolant flow rate through Tehran Research Reactor (TRR) core during coastdown transients. In this method, equations for torque and head as a function of speed and flow rate are derived. Then these equations are solved simultaneously in order to determine pump behaviour during coastdown. Eventually the effect of natural convection head at low speed is observed. This effect, during steady-state, is omitted compared to pump developed head. The effect is more pronounced when the coolant flow rate diminished to one-third or one-fourth of original flow rate. Consequently, at these flow rates, the natural convection head must be reckoned with. The obtained results indicate that natural convection head has clearly affected the coastdown flow time.

INTRODUCTION

The transients flow may be defined as any temporary variation in the pressure and discharge in the pipeline and in the speed and torque of the centrifugal pump. Transients are produced by starting and stopping the pump, by any changes in pump speed, and by the manipulation of valves [1]. In nuclear reactor design the precise evaluation of flow transient is an important factor. In this connection transients caused by power failure to the centrifugal pump had been investigated [2]. They considered natural convection head to be significant when the flow has decreased to low values. Transients due to power failure, starting pumps in idle loops, and the opening of an active discharge valve of pump have been studied by [3]. Flow coastdown in centrifugal pump systems was studied by [4]. He obtained experimental coastdown characteristic curves where the coolant flow rate reached to a lower value. Pump characteristics under unsteady condition was investigated by [5]. Flow transients caused by gravity flow in Tehran Research Reactor are investigated by [6]. He considered pump failure during normal operation. Two important parameters were used in the analysis. The initial potential energy stored in the reactor pool just before power cut off to pump and the initial kinetic energy in the release of coolant immediately after power cut off to the pump. The ratio of stored kinetic energy of coolant to the coolant stored potential energy is an effective energy ratio. This ratio played a key role in the analysis. In other study flow

coastdown of the TRR was considered and the results obtained from this model were compared with the existing experimental data [7]. In this study the ratio of kinetic energy in the pipeline to kinetic energy of the pump is defined as an effective energy ratio. The results show that the value of effective energy ratio is an excellent predictor of the pump performance in the event of transients. In a separate study the retarding torque during the TRR flow coastdown was measured and included in the derived model [8]. It is shown that the retarding torque resulted from the loss of electrical power to the canned motor is significant. This paper concentrates on the effect of natural convection head on the TRR coastdown transients flow time and aims to provide some information on flow rate and thermal cooling performance.

NOMENCLATURE

A	[m ²]	Fluid flow cross-section
C _d	[-]	Flow coefficient of orifice
D	[m]	Diameter
f	[-]	Friction factor
g	[m/s ²]	Gravity acceleration
h	[m]	Pump head
h _c	[m]	Convection head
H	[-]	Ratio of pump head to rated pump head
I _{pump}	[kg.m ²]	Pump moment of inertia
k	[-]	Loss coefficient of windage
K	[-]	Friction coefficient
KE	[J]	Kinetic energy
L	[m]	Length of flow path
M	[kg.m]	Torque
n	[rad/s]	Pump rotational speed
N _b	[-]	Number of baffle in heat exchanger
P _{CuS}	[W]	Power loss in stator
q	[kg/sec]	Flow rate
Q	[-]	Ratio of flow rate to steady-state flow
t	[sec]	Time
T	[-]	Ratio of elapsed time to the one-third time of loop
T _{elec.}	[kg.m]	Electrical torque
T _{hyd.}	[kg.m]	Hydraulically torque

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$T_{\text{mech.}}$	[kg.m]	Mechanical torque
w	[kg/(m ² .s ²)]	Specific weight
Special character		
β	[-]	ratio of orifice diameter to pipe diameter
ε	[-]	Ratio of effective energy stored in the pump
η	[-]	Efficiency
Φ_s	[-]	μ/μ_s
ρ	[kg/m ³]	Fluid density
Subscripts		
0		Conditions at time 0
bv		Butterfly valve
c		Core
cv		Check valve
e		Equivalent
elec		Electrical
f		Fluid
gv		Gate valve
hex		Heat exchanger
ht		Hold-up tank
hyd		Hydraulic
mech		Mechanical
R		Rated
s		Shell

FLOW TRANSIENT CONSIDERATIONS

There are many methods for controlling flow transients [9]. The kind of flow transient addressed in the present work is actually consequence of the coastdown flow transient. Under normal nuclear research reactor operation flow conditions, the buoyancy effects can be ignored. As the pumping power changes, the buoyancy effects on the transient can be neglected until the flow is reduced to only a few percent of the normal operating level. Therefore, even in the event of pump coastdown, the flow behaviour is dominated initially by the inertia term and the hydraulic resistance term [10]. **Figure 1** shows different flow coastdown stages.

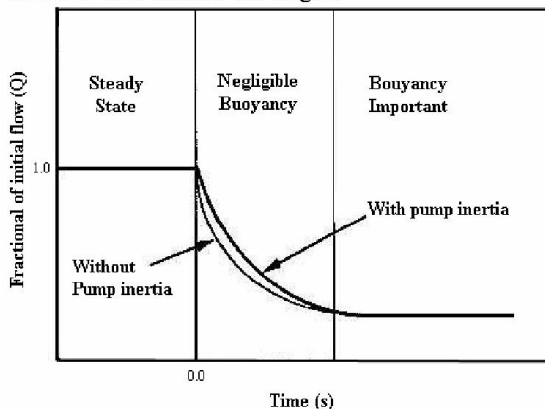


Figure 1 Different stages of flow coastdown

To correctly analyze the early stage of coastdown, negligible buoyancy, is very important. The behaviour of the

system in this stage is highly depends on pump inertia. In a previous analytical model [7] a ratio, kinetic energy in the piping system and kinetic energy of the pump, was defined for a piping system where all influencing parameters in the system were involved in the ratio (an effective energy ratio). This parameter, the effective energy ratio, is found to be a very accurate indicator of the pumping duration task. The velocity of flow during coastdown transient is determined analytically without the use of characteristics of the centrifugal pump. In deriving the model it was assumed that both the retarding torque and the developed head are proportional to the square of the pump speed. The two most important variables influencing flow coastdown transients are inertia of the rotating parts and inertia of the coolant fluid. These parameters are related to kinetic energy of the pump and kinetic energy of the fluid. Therefore $\frac{1}{2} \frac{dQ}{dT} + Q^2 = \frac{1}{(2\varepsilon T + 1)^2}$ represents system behaviour

during the event without using pump characteristic curves where an effective energy ratio is (ε). The detailed derivation of this relation is given in [7]. All of the variables used in this relation are normalized. Q is the ratio of the transient flow to steady-state flow, T is the ratio of elapsed time to the one-third time of the loop, and (ε) is the ratio of the energy in the fluid to the effective energy stored in the pump. It is worthy to note that the time scale is normalized with respect to the coolant fluid in the primary loop rather than one-third time of the pump. The effect in pump energy, when the fluid parameters are fixed, is then properly shown. The effective energy ratio (ε) has another physical meaning. The kinetic energy stored in the rotating parts of the pump during steady-state operation $KE_{\text{pump}} = \frac{1}{2} I_{\text{pump}} n_{(R)}^2$ and the kinetic energy stored in the

flowing coolant fluid $KE_{\text{fluid}} = \frac{1}{2} \sum \frac{L}{A} \left(\frac{w}{g} \right) q_{(R)}^2$. The ratio of stored energy of coolant fluid to the stored energy in the pump is also termed as an effective energy ratio. In other words, $\varepsilon = \frac{KE_{\text{fluid}}}{KE_{\text{pump}} n_{(R)}}$ where $\eta_{(R)} = \frac{\rho g h_{\text{pump}(R)} q_{(R)}}{M_{(R)} n_{(R)}}$. In the rated

efficiency, to avoid confusion, M is used to represents the ratio of steady-state torque to transient torque. When the energy stored in the rotating parts of the pump is very high, the effective energy ratio (ε) will be very small. In this physical situation the impeller of the pump will continue to pump the coolant fluid for a relatively long time. A relatively large value of an effective energy ratio (ε) indicates a pump with a small amount of stored energy, however. Or a pump which may not continue its pumping task for an extended time, but rather allows the coolant flow to decay rapidly under the influence of the friction forces in the primary cooling system. In this condition the impeller is therefore susceptible to turbining, since a low-energy impeller is normally one with small inertia. In deriving the model [7] it is assumed that the pumping head is always positive, and that it approaches zero as the effective

energy ratio (ε) becomes large. It must be emphasized that it is not physically true as it excludes the possibility of turbining. It nevertheless does not introduce a significant error in the analysis because a high effective energy ratio (ε) implies the presence of an impeller which offers little flow resistance. The equation of flow for the TRR considering individual components in the primary loop, as shown in **Figure 2**, is given by

$$\frac{1}{g} \left(\sum \frac{L_j}{A_j} \right) \frac{dq}{dt} + K_{cv} \frac{1}{2\rho g} \left(\frac{q}{A_{cv}} \right)^2 + K_{gv} \frac{1}{2\rho g} \left(\frac{q}{A_{gv}} \right)^2 + \frac{f(N_b+1)D_s}{2\rho g D \phi_s} \left(\frac{qP_i}{D, CB} \right)^2 + K_{sv} \frac{1}{2\rho g} \left(\frac{q}{A_{sv}} \right)^2 + K_{bv1} \frac{1}{2\rho g} \left(\frac{q}{A_{bv1}} \right)^2 + \frac{K_{pool}}{2\rho g} \frac{q^2}{A_{pool}^2} + \frac{q^2}{2A_c^2} \left[K + \frac{AfL_c}{D_e} + \left(1 - \frac{A_e}{A_c} \right)^2 \right] + K_{bv2} \frac{1}{2\rho g} \left(\frac{q}{A_{bv2}} \right)^2 + \frac{(1-\beta)^4}{2\rho g} \frac{q^2}{C_d^2 A_{orifice}^2} + \frac{K_{ht}}{2\rho g} \frac{q^2}{A_{ht}^2} + K_{piping} \frac{1}{2\rho g} \left(\frac{q}{A_{piping}} \right)^2 + K_{bends} \frac{1}{2\rho g} \left(\frac{q}{A_{bends}} \right)^2 = n^2 f_1 \left(\frac{q}{n} \right)$$

The detailed derivation of the above relation (i) is given in [8]. A brief explanation of the process will be given here, however. First of all the basic flow equation for the primary loop of the TRR is written. The first term of this flow equation will be pressure drop caused by inertial of the fluid in the primary cooling system while the second term take into account the entire pressure drop arising in the system. The centrifugal pump must provide enough head to compensate for the entire head and inertial losses in the system. The total pressure drop in the primary loop is sum of the pressure drop of the individual components which offer resistance change in the fluid system.

$$\Delta P_{cv} = K_{cv} \frac{1}{2\rho g} \left(\frac{q}{A_{cv}} \right)^2$$

Pressure drop due to check valve is

calculated by this relation and this is a general equation and can be used for orifice, gate valve, check valve...etc. Substituting all the components into the aforementioned basic flow equation will result in the final flow equation. Time dependent values of q must be known in order to know how flow rate varies with time. The equation of motion for the primary pump rotational speed is given by $\frac{1}{g} I_p \frac{dn}{dt} = T_{elec} - T_{hyd} - T_{mech}$. The individual

RHS terms are analyzed and then substituted for in the pump rotational speed. The final equation representing the TRR primary loop pump rotational speed

$$\frac{1}{g} I_p \frac{dn}{dt} = C f_2(n) - \frac{1}{s} (P_{Core} + P_{Cus}) \left(\varepsilon \frac{n}{\tau} \right)^2 \frac{n_{inst}}{n_{initial}^2} - \frac{q n f_1 \left(\frac{q}{n} \right)}{f_3 \left(\frac{q}{n} \right) f_4(n) \rho} - k_{mech} (n)^2$$

This equation (ii) predicts pump speed during coastdown. In order to study the influence of retarding torque on the Tehran Research Reactor flow coastdown transient, equations (i) and (ii) must be solved simultaneously.

ANALYTICAL METHOD

Since in Tehran Research Reactor there is a significant natural convection head a modification of these results is necessary. During steady-state operation the natural convection head, which is generally quite small in comparison in the pumping head, may be added up with the pumping head. In summing up the head in this fashion, it is implied that the

natural convection head is proportional to the square of the pump speed. Although this is quite arbitrary, it has, during the early stage of coastdown, little effect on the flow. However, after the coolant flow has decayed to possibly one-third or one-fourth of its initial value with a corresponding friction head drop to one ninth or one-sixteenth of the steady-state friction, the natural convection head must be taken into consideration.

The physical system, Tehran Research Reactor primary cooling system, to be analyzed is shown in **Figure 2**. It consists of several sections representing the centrifugal pump, heat exchanger, reactor pool, reactor core, orifice, hold-up tank, valves, and connecting piping. Tehran Research Reactor is a 5 MWth pool-type reactor with MTR type fuel elements of low enriched uranium (LEU). The reactor is cooled and moderated with light water. The coolant passes through the reactor core grid plate into a hold-up tank and then returns back into the reactor pool by a centrifugal pump through a heat exchanger.

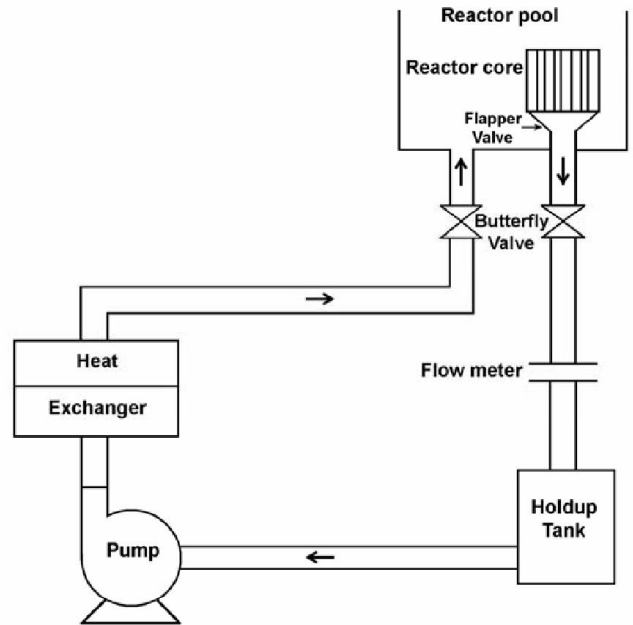


Figure 2 Primary cooling system of Tehran Research Reactor

Considering values of effective energy ratios (ε) up to about (ε) = 1, it is found that fraction of initial flow Q may expressed as

$$Q = \frac{1 + \varepsilon / 2 + \varepsilon^2 / 8}{1 + \varepsilon T} \tag{1}$$

in the approximate range $T > 1$. The dimensionless time $\left(T = \frac{t}{t_{1/3}} \right)$ where $t_{1/3} = \frac{2q_{(R)} \sum \frac{L_j}{A_j}}{g h_{p(R)}}$ determines whether the natural convection head should be considered. Obviously as this dimensionless time increases the flow rate Q decreases and the effect of natural convection is more significant. This effect is

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included in the differential equation whose homogenous solution is equation (1). This equation is

$$\frac{dQ}{dT_1} + Q^2 = H \quad (2)$$

with $Q(0) = 1 + \varepsilon/2 + \varepsilon^2/8$; $T_1 = \frac{\varepsilon T}{1 + \varepsilon/2 + \varepsilon^2/8}$; $H = h_c / h_{p(R)} \cdot A$

modified nondimensional time for ($\varepsilon > 1$). Solving for Q in equation (2) results

$$Q = \sqrt{H} \left\{ \frac{1 + \varepsilon/2 + \varepsilon^2/8 + \sqrt{H} \cdot \tanh \frac{\sqrt{H} \varepsilon T}{1 + \varepsilon/2 + \varepsilon^2/8}}{\sqrt{H} + (1 + \varepsilon/2 + \varepsilon^2/8) \cdot \tanh \frac{\sqrt{H} \varepsilon T}{1 + \varepsilon/2 + \varepsilon^2/8}} \right\} \quad (3)$$

As $H \rightarrow 0$, $Q \rightarrow \frac{(1 + \varepsilon/2 + \varepsilon^2/8)}{(1 + \varepsilon T)}$ which is the limiting

solution given in equation (1). Also

as $T \rightarrow \infty$, $Q \rightarrow \sqrt{H}$ signifying that the ratio of the square of the

two steady-state flows is equal to the ratio of the steady-state heads. Having done this modification the flow decays asymptotically to the free convection flow. To observe the whole trends of the phenomenon it seems appropriate to blend equation (1) where the early stage of coastdown is well demonstrated and equation (3) where the terminal stage of the natural convection flow is well shown. For the smaller values of effective energy ratio (ε) this will indeed be the case; but

with larger values of effective energy ratio (ε) there will be some discontinuity. To demonstrate this number curves are plotted in **Figure 3**.

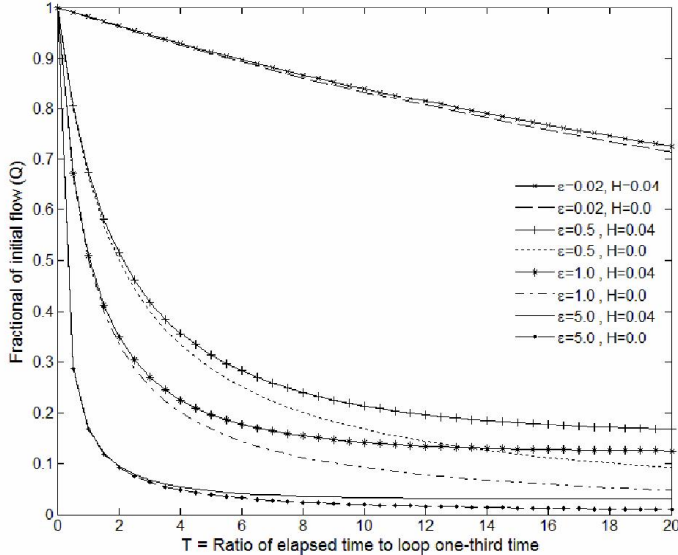


Figure 3 Analytical curves for coastdown to free convection flow

In the present study a value of ($H = 0.04$) is taken into consideration. In this figure two curves are shown for each value of effective energy ratio (ε). The upper most curves are shown for each set represents the flow decay to terminal free convection and the lower, as mentioned already, represents the

flow decay without thermal head convection. For the situation where the effective energy ratio is ($\varepsilon = 1$) it is noticed that the blending of the two curves is not perfect. This is shown in **Figure 3**. It is seen from the figure that a final free convection head of four percent of the steady-state head changes the terminal flow significantly. In addition to this, it is also clear from the figure that the coolant flow decays to a final value of $Q=0.2$ in place of zero flow rate. It must be mentioned that for values of effective energy ratio ($\varepsilon > 1$), this approach can not be used. This is because for this situation equation (2) is not representing until fairly high value of dimensionless time (T) are reached. It is appropriate to blend the natural convection flow into the early stage of flow by characterizing the terminal flow by the equation

$$\frac{dQ}{dT} + Q^2 = H \quad (4)$$

where as before ($H = h_c / h_{p(R)}$), and $Q(0) = 1$. The solution of equation (4) is given by

$$Q = \sqrt{H} \left(\frac{\sqrt{H} \tanh \sqrt{H} + 1}{\sqrt{H} + \tanh \sqrt{HT}} \right) \quad (5)$$

Equation $\frac{1}{2} \frac{dQ}{dT} + Q^2 = \frac{1}{(2\varepsilon T + 1)^2}$ represents the coastdown

flow well as long as $\frac{1}{(\varepsilon T + 1)^2} \gg H$ and

equation $Q = \sqrt{H} \left(\frac{\sqrt{H} \tanh \sqrt{H} + 1}{\sqrt{H} + \tanh \sqrt{HT}} \right)$ represents the flow well

when $H \gg \frac{1}{(\varepsilon T + 1)^2}$. The central section of the curve can however

be readily approximated. For the situation where effective energy ratio tends towards infinity,

equation $\frac{1}{2} \frac{dQ}{dT} + Q^2 = \frac{1}{(2\varepsilon T + 1)^2}$ blends well equation (5).

Actually it is the exact solution and is plotted in **Figure 3** for $H = 0.04$.

RESULTS AND DISCUSSION

Mathematical model developed in the present study is used to study the influence of natural convection head on coastdown transients flow time. Figure 3 shows that as the effective energy ratio increases the flow rate decreases to a lower rate but not zero. The above discussion has been concerned particularly with the single loop coastdown transient. There is a strong indication that the simplified approach studied here is enough for most applications. Also it will allow a substantial reduction in the time and work that is generally expended in the determination of the coastdown flow. In addition to this, it would appear that the same solution technique is applicable to multiple loop coastdown problems such as primary reactor systems containing a number of centrifugal pumps in parallel. Another important parameter that needs special attention is the mechanical loss must be accounted for during the coastdown.

Figure 4 shows different values of mechanical loss in the

event. The electrical torque developed during coastdown necessitates a cumbersome method for evaluation. The losses or retardation torque must be evaluated as accurately as possible during the coastdown. This is because during the event this is the only torque available in the system for accelerating mechanical load. In general, skin effect is characterized by a reduction of the effective area of cross-section of the rotor cage. This is caused by the current flows through the least impedance path of the rotor bar surface. During coastdown, slip frequency increases. This in turn increases the impedance of each motor phase. As a consequence the effective electrical torque decreases. Moreover, at high slips and (currents), reduction of the leakage flux path saturation causes a reduction of stator and rotor leakage inductances. The influence of magnetizing saturation for higher slips is negligible. Nevertheless the effect of decaying magnetic flux and angular velocity is included. Stray losses (eddy current) are already included in the core losses. When the power is cut-off from the motor the current reduces. This current produces a magnetic flux instantaneously. As a consequence the induced magnetic field in the rotor changes direction with the current frequency. Due to hysteresis in rotor, the iron core lags the new direction which prevents rotor to attain actual speed relative to frequency. The induced current in the rotor opposes the motion of the rotor and consequently reduces the effective rotor torque.

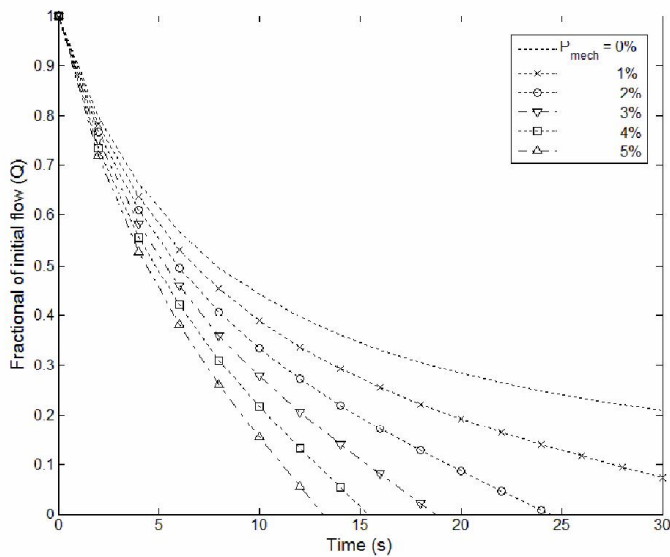


Figure 4 Variation of the TRR flow coastdown characteristic with mechanical losses (motor and pump)

In studying the interaction between the impeller and the coolant, it is necessary to take into account the driving head developed by the pump impeller, the dynamic interaction of the coolant and impeller, the frictional resistance to fluid circulation, and the inertia of both the impeller and the coolant. In some systems there will also be a natural convection head which may either assist or impede the flow. In many reactor primary loops it is found that during normal operation the natural convection head is small in comparison to the pumping head, so that it may be disregarded during the early stage of flow decay. When the flow has been significantly reduced the natural convection head should be taken into account. Therefore in working out this problem, the effect of natural

convection head is first neglected and the solution then modified to take into account the natural convection force. The crux of the analytical solution lies in the assumption that both the retarding torque on the impeller and the developed head are proportional to the square of the pump speed. **Figure 4** shows the effect of the mechanical loss (motor and pump) on the Tehran Research Reactor flow coastdown characteristic decay curves. It is clear from the figure that in the early stage of the flow coastdown the effect of mechanical loss is not significant. This effect is more and more significant as the flow rate decreases. Flow coastdown characteristic decaying curves are necessary for the overall safety of nuclear research reactors safe operation as soon as pumping power cut-off. Consequently accurate flow coastdown characteristics curves highly depends on identifying and considering as many power loss quantities as possible. The electrical torque accompanied by coastdown transients necessitates a more complex method of evaluation. **Figure 4** also shows that the effect of mechanical power loss becomes more obvious after early stage of the flow coastdown. Perhaps more experimental work will reveal the physical situation in this region.

Physical quantities	Arker and Lewis (1956)	Yokomura (1969)	Grover and Koranne (1981)	Tehran Research Reactor (1986)
NR (RPM)	3580	1470	Unknown	1450
HR (m)	14.49	41.9	57.79	30.480
QR (m ³ /s)	0.436	a 0.1259 b 0.0290 c 0.1256 d 0.0279	0.01572	0.1387
η (%)	86	75.6	83	83
I_p (kg.m ²)	0.8	3.7	a 0.2 b 0.5 c 1.0	0.2
$\sum \frac{L}{A}$ (m ⁻¹)	38.56	959	d 6916 e 13832 f 27664	1717
ϵ	0.342	0.1131	a(e) 0.3250 b(e) 0.1300 c(e) 0.0650 d(a) 0.0161 e(a) 0.3250 f(a) 0.6506	0.947

Table 1 represents design data of some of flow coastdown

In table some of the work of the existing data is briefly mentioned in order to make the comparison between the present model and the others more understandable. The table is taken from [6] for the sake of comparison. The results of the present model are compared with the results of the existing results. **Figure 5** shows a comparison of obtained results from the present study with the works of other researchers revised in this work.

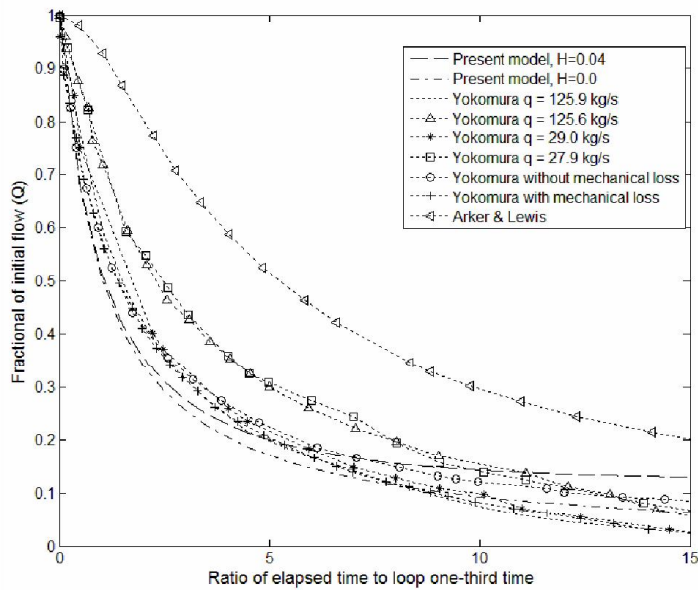


Figure 5 comparison of the present model with other similar works existing in the literature
The present model shows good agreement with the similar flow coastdown results.

CONCLUSION

Effect of natural convection head is needed for the overall safety of nuclear research reactor safe operation. As is seen from **Figure 3** the natural convection head causes coolant flow to decay towards complete rest with a lower flow rate. Or as a consequence it takes longer time to remove the passive heat in the core. In addition to this, the significant influence of the natural convection head can be observed in later stage of the transient. As time passes, the difference in flow rate for upper and lower limits becomes even greater.

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