International Conference
Nuclear Energy for New Europe 2004
Portorož • Slovenia • September 6-9

port2004@ijs.si
www.drustvo-js.si/port2004
+386 1 588 5247, fax +386 1 561 2276
PORT2004, Nuclear Society of Slovenia, Jamova 39, SI-1000 Ljubljana, Slovenia

Physical Model of Reactor Pulse

Andraž Petrović, Matjaž Ravnik
"Jožef Stefan" Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
matjaz.ravnik@ijs.si, josef_ka@email.si

ABSTRACT

Pulse experiments have been performed at J. Stefan Institute TRIGA reactor since 1991. In total, more than 130 pulses have been performed. Extensive experimental information on the pulse physical characteristics has been accumulated. Fuchs-Hansen adiabatic model has been used for predicting and analysing the pulse parameters. The model is based on point kinetics equation, neglecting the delayed neutrons and assuming constant inserted reactivity in form of step function. Deficiencies of the Fuchs-Hansen model and systematic experimental errors have been observed and analysed. Recently, the pulse model was improved by including the delayed neutrons and time dependence of inserted reactivity. The results explain the observed non-linearity of the pulse energy for high pulses due to finite time of pulse rod withdrawal and the contribution of the delayed neutrons after the prompt part of the pulse. The results of the improved model are in good agreement with experimental results.

1 INTRODUCTION

In 1991 TRIGA reactor at J. Stefan Institute was equipped for pulse mode operation. Since than more then 100 pulses were performed [1]. Normally, the adiabatic Fuchs -Hansen model (abbreviated: F-H model) is used for predicting the pulse parameters and in safety analysis [2]. When the measured pulse parameters such as maximal power and total released energy are compared to F-H model certain systematic differences are observed [3]. Main drawbacks of F-H model are neglecting of delayed neutrons and step insertion of reactivity. Neglecting of the temperature dependence of negative temperature reactivity coefficient and of specific heat capacity of the fuel contribute to the inaccuracy of the model as well. Recently, the F-H model was improved by the authors.

2 IMPROVED MODEL

The model is based on complete set of point kinetics equations [2]:

$$\frac{dP(t)}{dt} = \frac{\rho(t) - \beta}{l} P(t) + \sum_{i=1}^{6} \lambda_i C_i(t) \tag{1}$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i(t)}{l} P(t) - \lambda_i C_i(t) \tag{2}$$

P(t) – power of reactor at time t
ρ(t) – reactivity at time t
l – prompt neutron generation time
β – effective delayed neutron fraction; $\sum_{i=1}^{6} \beta_i = \beta$
λi – delayed neutron precursor's decay constant
Ci – delayed neutron precursor concentration.

Like F-H model, also the improved model assumes adiabatic approximation for heat transfer. It means that all energy generated in the pulse is used for heating the fuel. With this assumption, the reactivity *ρ(t)* in eq.(1) can be written as:

$$\rho(t) = \rho_0(t) - \frac{\alpha(T)}{mc_p(T)} \int P(t')dt' \tag{3}$$

where

α(T) – fuel temperature reactivity coefficient
m – total in mass of fuel in reactor
cp(T) – specific heat capacity of fuel.

The improvements in our model with respect to F-H are as follows:

a.) delayed neutrons (6-group approximation)
b.) actual travel time of the pulse rod
c.) reactivity addition takes into account pulse rod integral reactivity curve
d.) temperature dependence of negative temperature reactivity coefficient
e.) temperature dependence of specific thermal capacity of the fuel.

The model is programmed in Mathematica [4], using Runge-Kutta method for numerical solutions [5] of eqs. (1-3). The results of the improved model are presented in figure 2.1 in comparison to F-H model and to the measurements for the first series of pulses (1-7) performed in 1991.

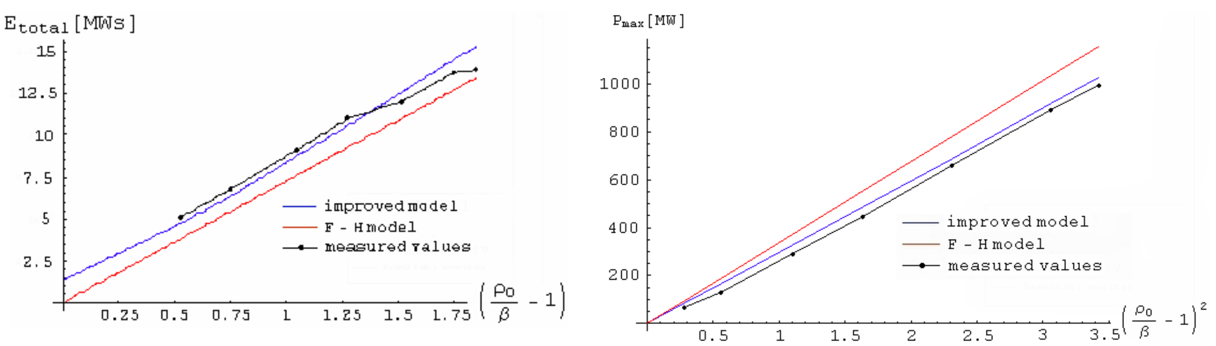

Figure 2.1: Comparison between measured values of pulse maximum power and total released energy, values calculated with F-H model and results of improved model

2.1 Contribution of delayed neutrons

One can see from the figure 2.1, that neither improved model nor F-H model can calculate values of released energy in the pulse correctly through the whole interval of inserted reactivity. For that reason we first consider pulses with small inserted reactivity. Improved model calculates values of released energy of the pulse up to 2.5 β better than F-H model. Values calculated with F-H model are systematically smaller than measured values. The reason for this discrepancy is neglecting of delayed neutrons. In order to test this assumption, we neglect delayed neutrons in the improved model. Results are shown in figures 2.2 a and b.

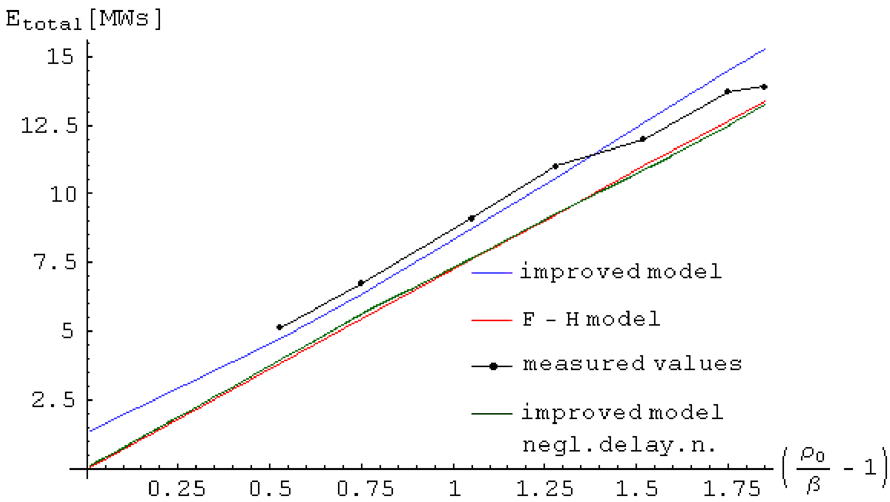

Figure 2.2 a): Comparison between measured values of total released energy in the pulse and values calculated by F-H model, improved model and model that neglects delayed neutrons.

Note that F-H model curve and the curve of improved model with neglected delayed neutrons are practically identical

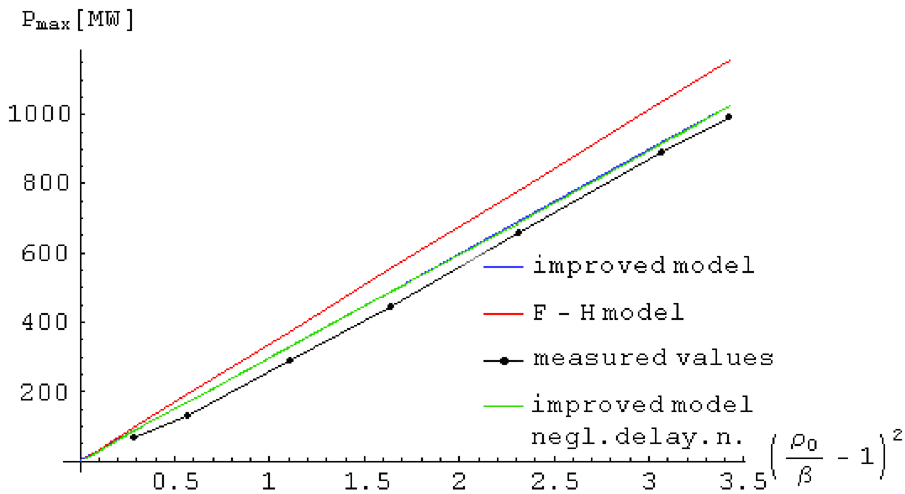

Figure 2.2 b): Comparison between measured values of maximal power in the pulse and values calculated by F-H model, improved model and model that neglects delayed neutrons.

The power released during the pulse is presented in figure 2.3. The measured value is compared to our improved model with and without delayed neutrons. It can be observed that the model taking into account delayed neutrons correctly interprets the tail of the pulse where their contribution prevails. The oscillations in measured signal in the tail are due to detector noise (influence of 50 Hz AC voltage).

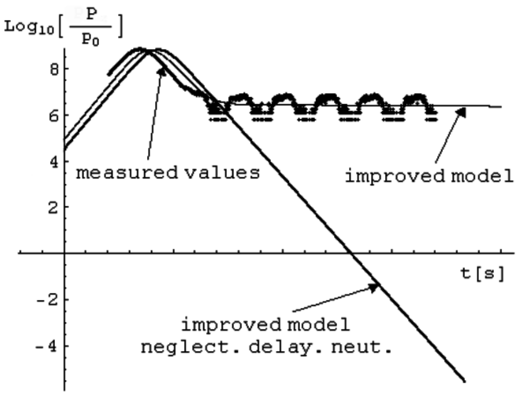

Figure 2.3: Power as a function of time for measured values, improved model and model that neglects delayed neutrons

Released energy in pulse is obtained by integrating power with time. If integration time is extended over the tail the delayed neutrons may not be neglected. On the other hand the delayed neutrons do not influence the maximal power in the pulse. Maximum power of pulse occurs 0.1 sec – 0.2 sec after begining of the pulse. In this short period of time only small fraction of delayed neutrons is released. This small quantity of neutrons does not contribute to the maximal power of the pulse significantly.

2.2 Finite time of pulse rod withdrawal

Actual speed of pulse rod withdrawal is included in the improved model. Improved model considers constant acceleration of pulse rod during its movement from bottom to top position. To study the effect of the rod motion, this assumption was replaced by step change in reactivity due to the pulse rod, like in F-H model. Results are shown in figure 2.4 a. and figure 2.4 b.

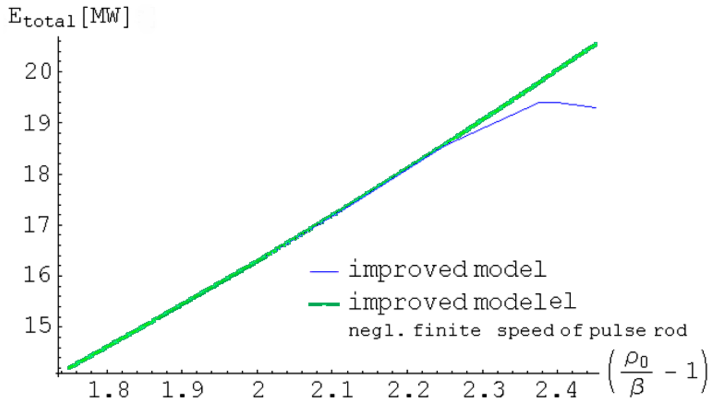

Figure 2.4 a): Comparison of total released energy in the pulse calculated with improved model and model that neglects contributions of finite speed of pulse rod

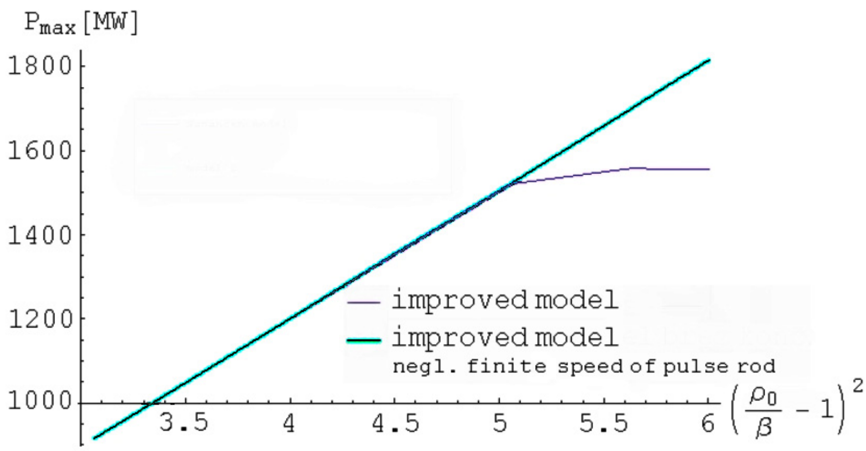

Figure 2.4 b): Comparison of maximal power in the pulse calculated with improved model and model that neglects contributions of finite speed of pulse rod

One can see from figure 2.4 a. that improved model predicts "saturation" or "break" above inserted reactivity ~ 3.2 β, i.e. the maximum power does not increase with inserted reactivity any more above certain value.

Physical background of the "break" can be explained by observing on the same diagram the time dependence of power, inserted reactivity and total reactivity (figure 2.5), for small and high inserted reactivity.

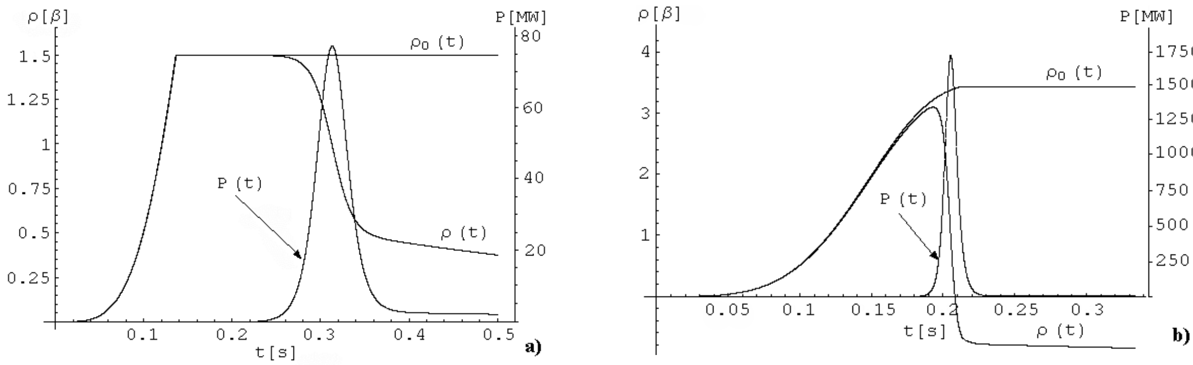

Figure 2.5: Time dependence of power, inserted reactivity and reactivity of the system for small a) and high b) inserted reactivity calculated by *improved model*

The important difference between pulses made by small or high inserted reactivity is that maximum power of the big pulse occurs sooner than maximum power of small pulse (figure 2.5). Figure 2.5 a. shows, that in case of small inserted reactivity pulse rod reaches top position before the pulse reaches maximum power. This means, entire inserted reactivity can be used by the system, before negative temperature effects reduce the pulse. In case of high inserted reactivity the pulse overtakes the pulse rod. As a result, a fraction of inserted reactivity is wasted, because negative temperature effect starts to reduce the pulse before it reaches the maximum. This retardation and reduction of pulse is manifested in smaller maximum power. If contribution of finite speed of the pulse rod is not considered in physical model, pulse never overtakes pulse rod and the "break", can not be predicted by such a model (F-H model). It is expected that inserted reactivity should be at least 3.2 β in order to observe "break" on TRIGA reactor at J. Stefan Institute.

3 RESULTS OF IMPROVED MODEL

The effect of pulse "break" at high inserted reactivity is described in previous chapter. This phenomenon is observed in the model at approximately 3β and could be in principle experimentally verified as such inserted reactivities are technically feasible at our reactor. However, pulsing above approximately 2.5β is normally administratively prohibited. Phenomena above 3β can not be experimentally verified at our reactor. Namely, if the reactivity is further increased, another phenomenon is observed in the improved model. Figure 3.1. presents that another or "companion" pulse appears if reactivity is sufficiently high.

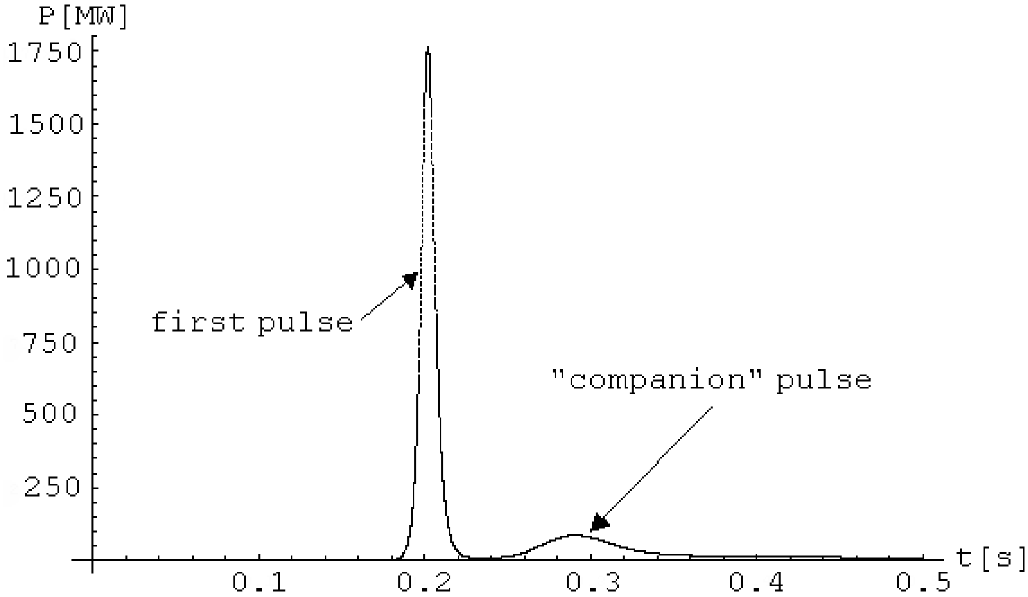

Figure 3.1: Power course predicted by improved model for inserted reactivity 6 β

The easiest way to explain "companion" pulse is to put on the same diagram time dependence of power, the position of the pulse rod and reactivity of the system (figure 3.4):

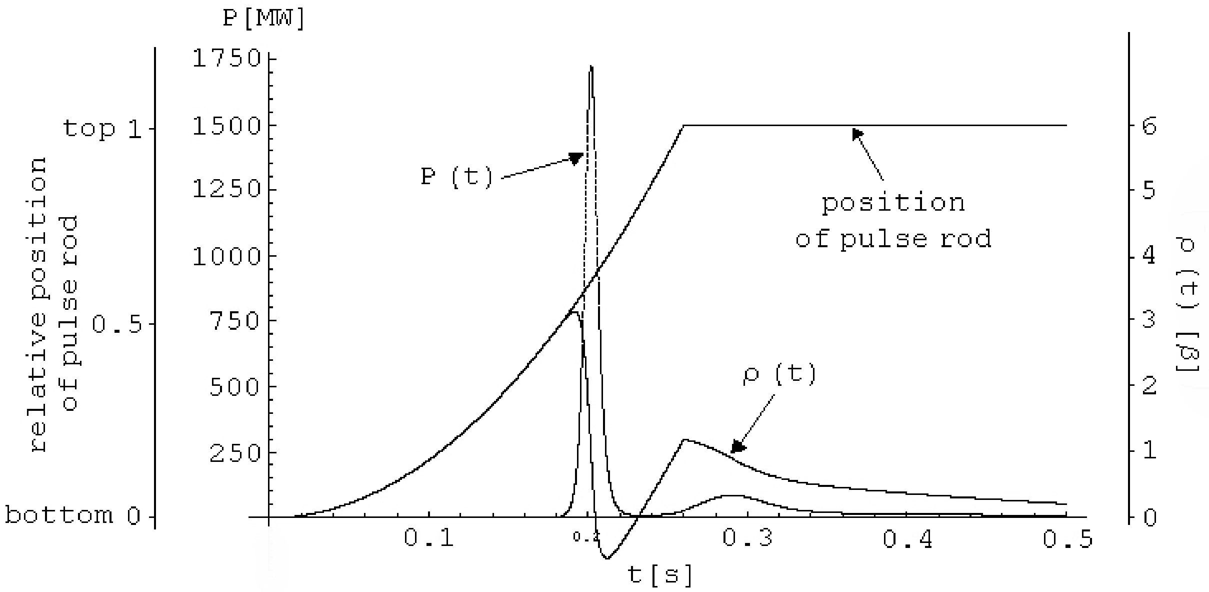

Figure 3.4: Power, pulse rod position and reactivity of the system for inserted reactivity 6 β

After the maximum power is reached in the first pulse, the power of the reactor quickly drops. As a result negative term $k(T)\int_0^t P(t')dt'$ in (1) is not increasing any more. We can see in figure 3.4 that reactivity is still inserted in the system as pulse rod has not yet reached its top position. As a result, $\frac{dP(t)}{dt}$ becomes positive again leading to power increase, which is manifested as a "companion" pulse. Let us note that the phenomenon is not limited to pulsing in TRIGA reactor but may be expected also in reactivity excursion transients if the reactivity is constantly added during the transient. Two subsequent power excursions in Chernobyl accident could be explained by this phenomenon.

4 CONCLUSIONS

Although improved model is still rather simple, it can be applied for calculating the pulse parameters better than Fuchs-Hansen model. Next step for understanding reactor behavior in pulse conditions would be measurement of non-linear effects at high inserted reactivity. There are two possible approaches:

a) It is possible to increase inserted reactivity of the reactor until pulse overtakes the pulse rod. Rough prediction is that inserted reactivity needed for observation of the effect is around 3 β. Maximum allowed inserted reactivity should be increased which would require extensive additional safety analysis.

b) More simple approach without increasing maximum allowed inserted reactivity would be to reduce the pulse rod speed by reducing pressure in the pneumatic mechanism of the pulse rod.

REFERENCES

[1] J. Stefan Institute TRIGA reactor log-book

[2] George I. Bell, Samuel Glasstone, Nuclear Reactor Theory. (Litton Educational Publishing, INC, 1970)

[3] M. Ravnik, Reactor Physics of Pulsing: Fuchs-Hansen Adiabatic Model. http://www.rcp.ijs.si/~ric/pulse_operation-s.html (17.1.2004).

[4] Mathematica: ver. num. 5.0.0.0, Wolfram Research, Inc.

[5] Zakrajšek Egon, Uvod v numerične metode, Društvo matematikov, fizikov in astronomov Slovenije, 1998.