EXPERIMENTAL STUDY ON DENSITY-WAVE OSCILLATIONS IN TWO IDENTICAL CHANNELS

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ABSTRACT

Density-Wave instabilities in a system of two identical heated channels were experimentally studied in a forced circulation water loop.

In-phase and out-of-phase oscillations were observed and its stability boundaries determined.

The experimental data were compared with calculations based on a previously developed analytical model. Excellent agreement was found in the prediction of the oscillation modes and the stability boundary for in-phase oscillations. For out-of-phase oscillations the system was found to be more stable than expected.

1. INTRODUCTION

A number of analytical and experimental studies have dealt with Density-Wave Oscillations (DWO) in boiling multichannel systems [1,2].

It is well known that a system of N parallel heated channels presents N normal modes of oscillation. Each of them stands for the channel variables oscillating with certain phase differences and amplitude ratios. Different experimental results have been reported concerning the mode of oscillation that is activated [3-6].

For a two-identical-channel system two normal modes occur, one of them is the in-phase mode and the other is the out-of-phase one. In the former the variables of the two channels oscillate with the same phase and amplitude, while in the latter they oscillate with a 180 degrees phase shift but also with the same amplitude [7-11]. For a system with concentrated pressure drops a simple expression was derived in reference [11] to predict the stability limits of the two normal modes. It was shown that the system is stable if:

$$N_{PCH} - N_{SUB} < \frac{\tau}{2}\left[1 + \frac{2}{N_{SUB}}\right] - \frac{5}{2} + \left\{\left[\frac{\tau}{2}\left(1 + \frac{2}{N_{SUB}}\right) - \frac{5}{2}\right]^2 + \tau\right\}^{1/2} \qquad (1)$$

where τ should be replaced by τ_T or τ_P to obtain the stability condition for the in-phase or out-of-phase modes respectively. The friction parameters τ_T and τ_P are defined as:

$$\tau_T = \frac{2(K_I + K_E + K_i + K_e)}{K_E + K_e + 1} \qquad (2)$$

$$\tau_P = \frac{2(K_i+K_e)}{K_e + 1} \tag{3}$$

In these equations the friction coefficients are defined as $K=\Delta P/\rho u^2$ and the subscript indicates the region of the system where the pressure drop occurs. For a system of two channels connected to inlet and outlet plena, K_I is the friction coefficient at the entrance of the inlet plenum, K_E is located at the exit of the outlet plenum and K_i and K_e are the friction coefficients at the inlet and outlet of the heated channels respectively.

It was also shown that for τ_T smaller than τ_P the system is more unstable for in-phase oscillations. The reverse occurs for τ_P smaller than τ_T.

The present work shows the results of the experiments carried out in order to assess the validity of such analytical model.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Boiling Loop

A schematic diagram of the experimental loop is shown in figure 1. It is a forced convection loop with deaerated water at nearly atmospheric pressure as test fluid. The fluid is circulated by a centrifugal pump from an open tank. In the tank there is a condenser-subcooler which works with cooling water. Downstream of the pump the flow splits in two paths. Most of the flow goes through the by-pass, in order to maintain a constant pressure drop across the test section. The flow rate through the by-pass was at least 10 times larger than the flow rate through the test section. This by-pass to test section flow rate ratio is sufficiently high to ensure a constant pressure drop even with oscillating flows [5]. Both streams then converge to a single path through the control valve and return to the tank.

2.2 Test Section

The test section consists of an inlet valve, an inlet plenum, two heated channels and outlet plenum and valve. There is an additional by-pass connecting both plena but it was maintained closed in all the experiments reported herein.

The inlet and outlet pipes are 60 mm ID. The plena consists of cylinders 152 mm ID and 100 mm in height. Both heated channels are connected to their sides by 25 mm ID tubing. At the entrance and exit are located the inlet and outlet channel valves. In each channel, after turning an elbow, the fluid flows upwards through the vertical uniformly heated section which has annular geometry. It consists of a 25 mm ID glass tubing with a 9.5 mm OD, 1000 mm heated length joule heater centered in the inside. The heaters are connected to a DC power supply, and its resistances are paired to provide differences below 1% in the power given to each channel.

2.3 Instrumentation

The fluid temperature at the inlet and outlet plena and at the exit of the heated channels was measured with Chromel-Alumel thermocouples. The flow rate in each channel was measured at the inlet of the heated section by means of orifice plates and variable reluctance type differential pressure transducers which proved to give a sufficiently fast response. The flow meter outputs and the inlet temperature signal were sent to a personal computer and the data were stored in diskettes for off-line analysis. Sample intervals between 0.1 and 0.5 seconds were used.

2.4 Resistance Coefficients

Frictional pressure drops play a key role in the density-wave instability phenomenon. In order to have variable and known resistance coefficients the valves of the loop were calibrated.

The inlet and outlet channel valves are of the spherical type of 1" diameter. The valve at the entrance of the inlet plenum and the one at the exit of the oulet plenum are also spherical but of 2" diameter. Both were calibrated in independent loops. The calibration consisted in measuring the pressure at three stations upstream of the valve and at three stations downstream for different flow rates. With the values of the non-recoverable pressure drops and flow rates the resistance coefficients were calculated, for different valve openings.

The above-mentioned head losses were made greater than the distributed frictional pressure drops and other minor losses, in order to meet the model requirements.

2.5 Experimental Procedure

A set of experiments were run adjusting the openings of the valves to establish the prescribed friction parameters, τ_T and

τ_p.

The flow rates through the heated channels and the by-pass were then adjusted by means of the flow rate control valve and the by-pass valve. In such conditions, stable and oscillating situations were recorded for different powers by slowly varying the inlet temperature.

This procedure was repeated for different values of the friction parameters.

3. RESULTS

In-phase and out-of-phase oscillations were observed with the above-mentioned procedure. In both cases the amplitude of the flow rate oscillations in both channels were roughly equal and the phase differences were almost equal to 0 and 180 degrees respectively.

The observed oscillation periods were between 12 and 16 sec for in-phase instabilities and between 8 and 10 sec for out-of-phase ones. The residence time of a particle in the heated section was between 5.5 and 7.0 sec. With this correspondence the instabilities were classified as of the density-wave type.

In the in-phase case the oscillating region is between the points where the by-pass and the test section lines divide and recombine. In the out-of-phase case the total flow rate remains constant, therefore the oscillating region is between the two plena. This difference seems to cause the in-phase periods to be longer than the out-of-phase ones.

Figures 2 and 3 show typical traces of the dimensionless inlet flow rates, that is the instantaneous flow rates divided by the stable mean flow rates for such conditions. In figure 2 an in-phase oscillating condition is shown and in figure 3 an out-of-phase one.

Experimental results of the stability boundary are shown in figures 4, 5 and 6. Experimental stable and unstable situations are plotted in a subcooling number N_{SUB} versus phase change number N_{PCH} plane. The analytical predictions, calculated with the experimental values of the friction parameters, are also plotted, i.e. no adjustable parameters are used. Figures 4 and 5 correspond to in-phase oscillations. An excellent agreement was found between experimental and analytical results, which was a common feature of all the tests ran with τ_T smaller than τ_P. Figure 6 presents a typical out-of-phase case. In contrast with the in-phase tests, the system showed to be much more stable than the analytical predictions.

Figure 7 shows the oscillation mode occurring for different values of the friction parameters, in a τ_P versus τ_T plane. According to the model the points above the $\tau_P=\tau_T$ line should correspond to in-phase oscillations and below the line to out-of-phase ones. All the experimentally observed oscillations are in the half-plane predicted by the model.

4. CONCLUSIONS

An experimental study was carried out to assess the validity of a previously developed theoretical model for density-wave instabilities in a system of two identical heated channels.

In agreement with the model the oscillation modes observed were the in-phase and the out-of-phase ones.

The stability boundaries for in-phase oscillations were found to be in excellent agreement with the theoretical predictions.

For out-of-phase instabilities the experimental system was more stable than expected. The difference could not be explained with the present model and requires further examination.

Under the experimental conditions studied the model was found to be reliable in the prediction of the oscillation mode occurring.

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NOMENCLATURE

LATIN LETTERS

h: specific enthalpy

K: resistance coefficient = $\Delta p/\rho u^2$

N_{PCH}: phase change number = $\frac{Q}{W} \cdot \frac{v_{FG}}{v_F h_{FG}}$

N_{SUB}: subcooling number = $(h_F - h_i) . \frac{v_G}{v_F h_{FG}}$

p: pressure

Q: power

u: flow velocity in axial direction

v: specific volume

W: mass flow rate

GREEK LETTERS

Δ: difference

ρ: density

τ: friction parameters defined in (2) and (3)

SUBSCRIPTS

e: conditions at the outlet of the channel

E: conditions at the outlet of the system

f: saturated liquid

fg: transfer from liquid to vapor

i: conditions at the inlet of the channel

I: conditions at the inlet of the system

0: steady state

FIGURE CAPTIONS

Figure 1. Schematic diagram of the experimental apparatus.

Figure 2. Typical traces of in-phase flow oscillations. The dimensionless flow rate of both channels are plotted against time.

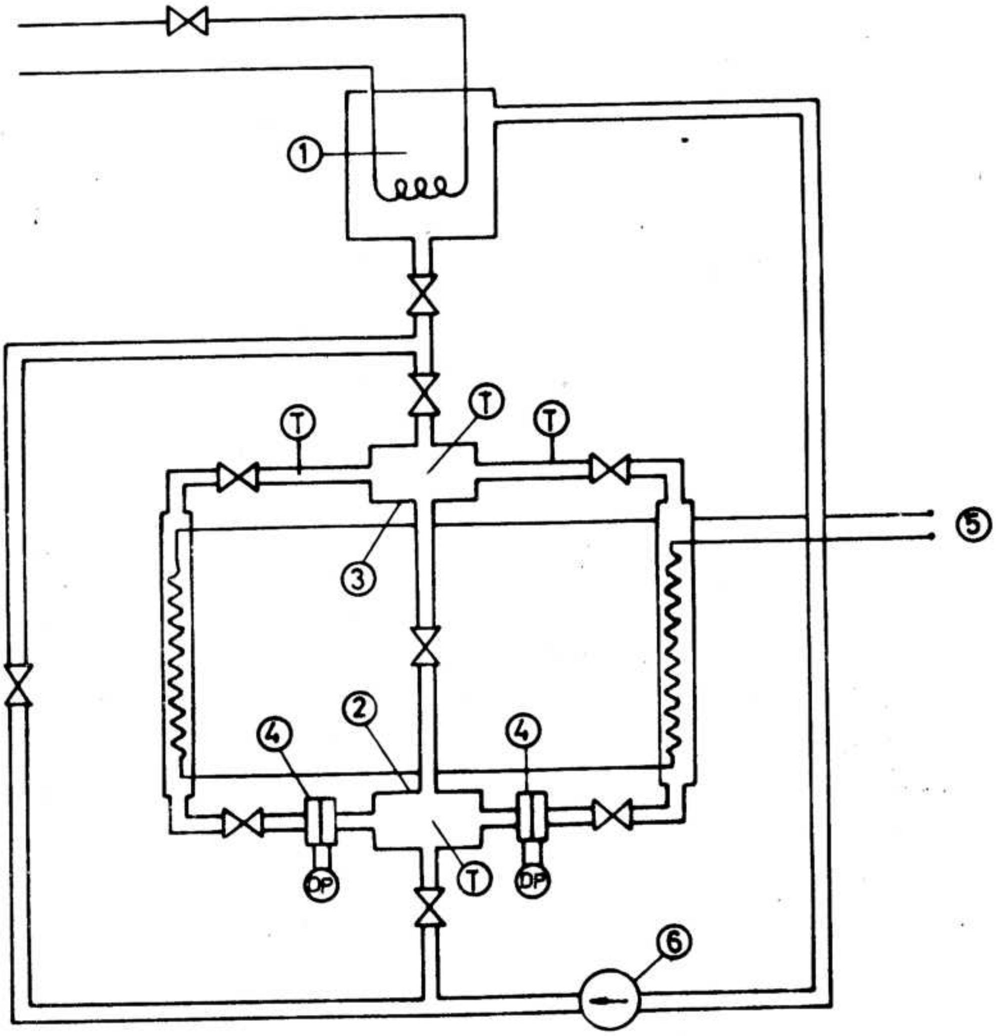
Figure 3. Typical traces of out-of-phase flow oscillations.

Figure 4. Stability boundary of an in-phase-unstable system with friction parameters $\tau_T = 8.0$ and $\tau_P = 15.0$. Experimental stable and unstable situations and the analytical prediction are plotted.

Figure 5. Stability boundary of an in-phase-unstable system with $\tau_T = 3.5$ and $\tau_P = 7.3$.

Figure 6. Stability boundary of an out-of-phase-unstable system. The values of the friction parameters are $\tau_T = 3.5$ and $\tau_P = 2.2$.

Figure 7. Oscillation mode map. In-phase and out-of-phase oscillations are plotted in a τ_P vs. τ_T plane.



① CONDENSER-SUBCOOLER

② INLET PLENUM

③ OUTLET PLENUM

④ ORIFICE

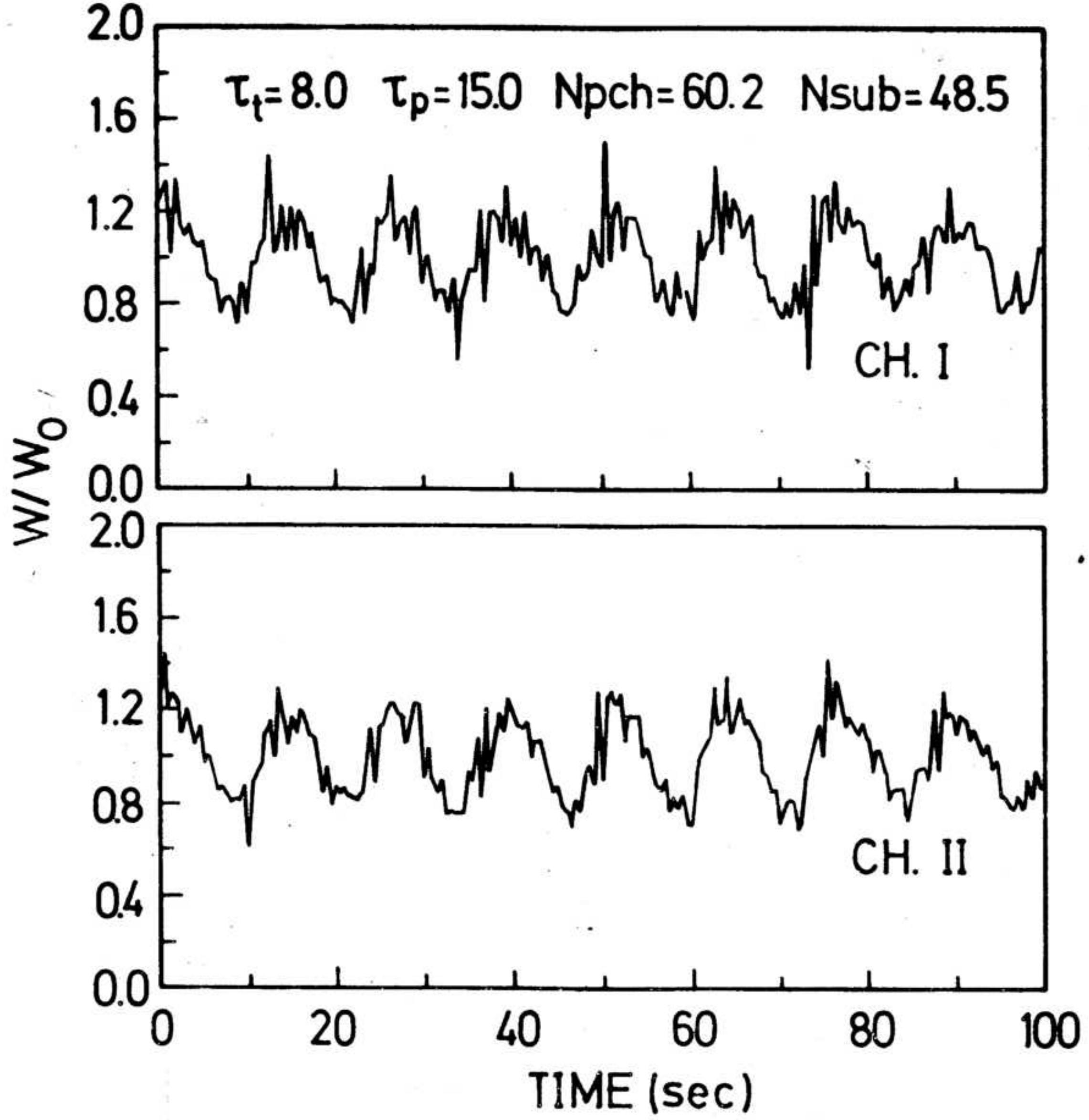
⑤ DC POWER SUPPLY

⑥ PUMP

Ⓣ C.A THERMOCOUPLE

(DP) DIFFERENTIAL PRESSURE TRANSDUCER

⋈ VALVE



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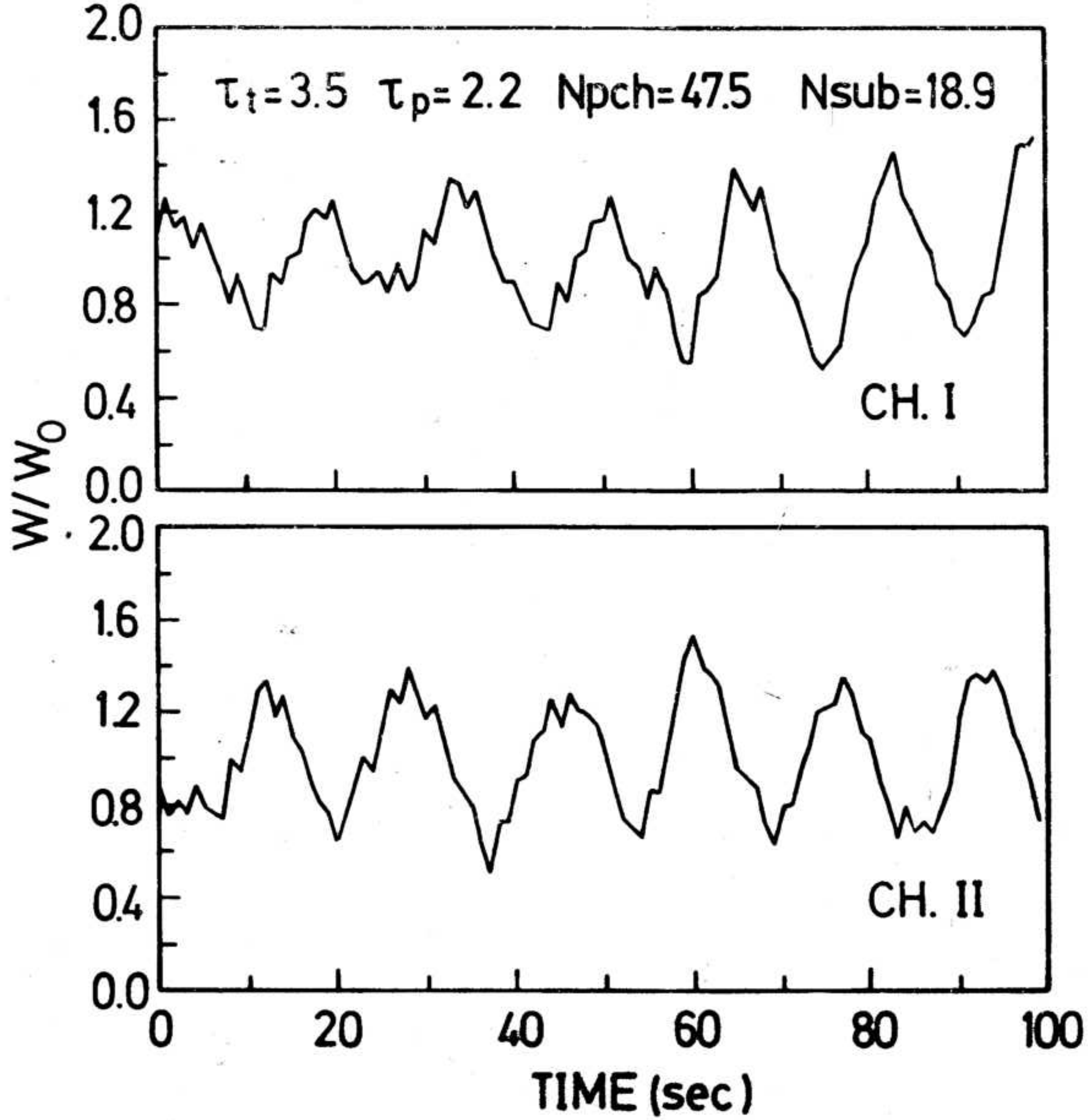
CH. I
CH. II
W/W0
2.0
1.6
1.2
0.8
0.4
0.0
0
20
40
60
80
100
TIME (sec)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CH. II
W/W0
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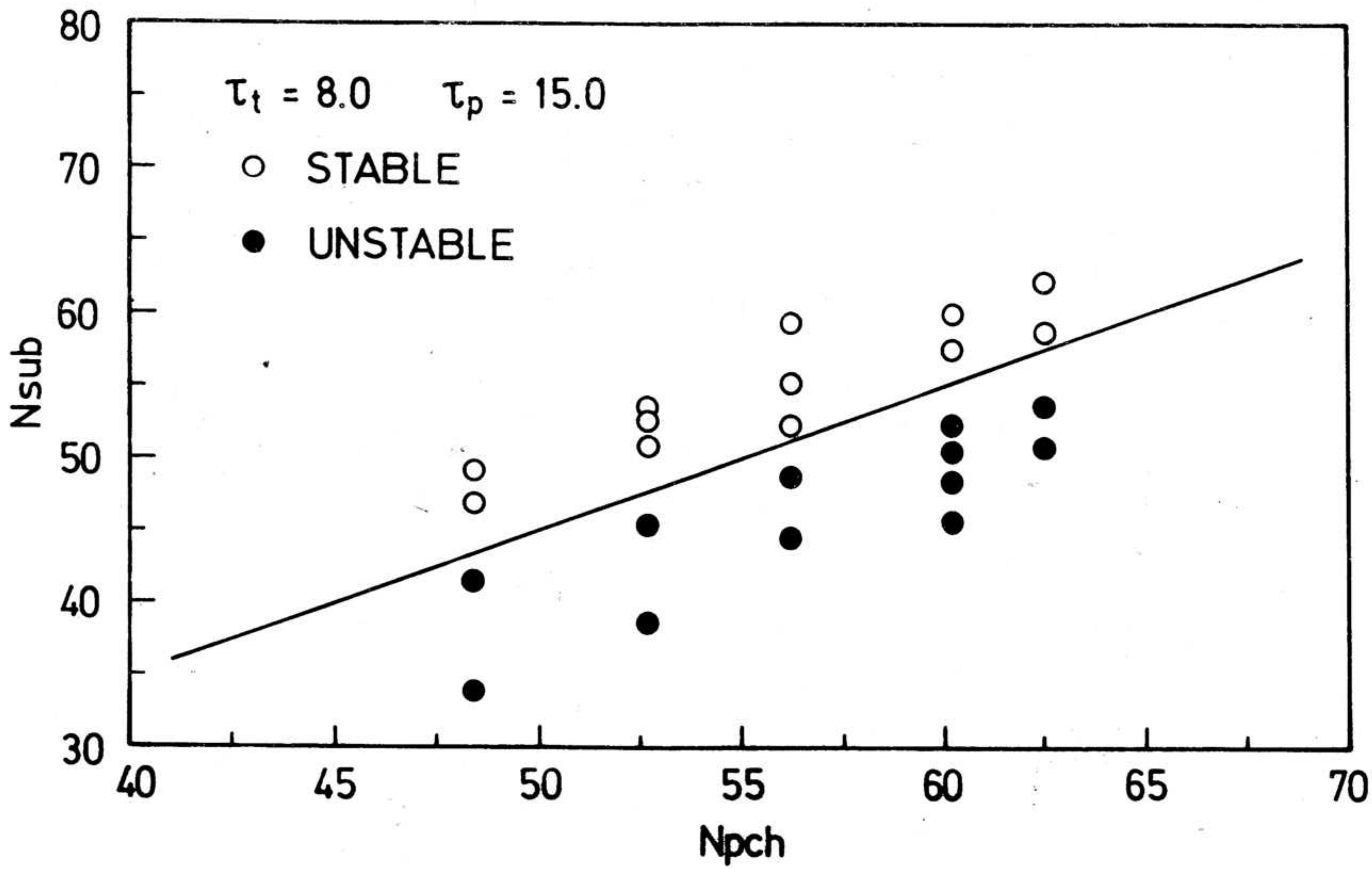
1.6
1.2
0.8
0.4
0.0
0
20
40
60
80
100
TIME (sec)



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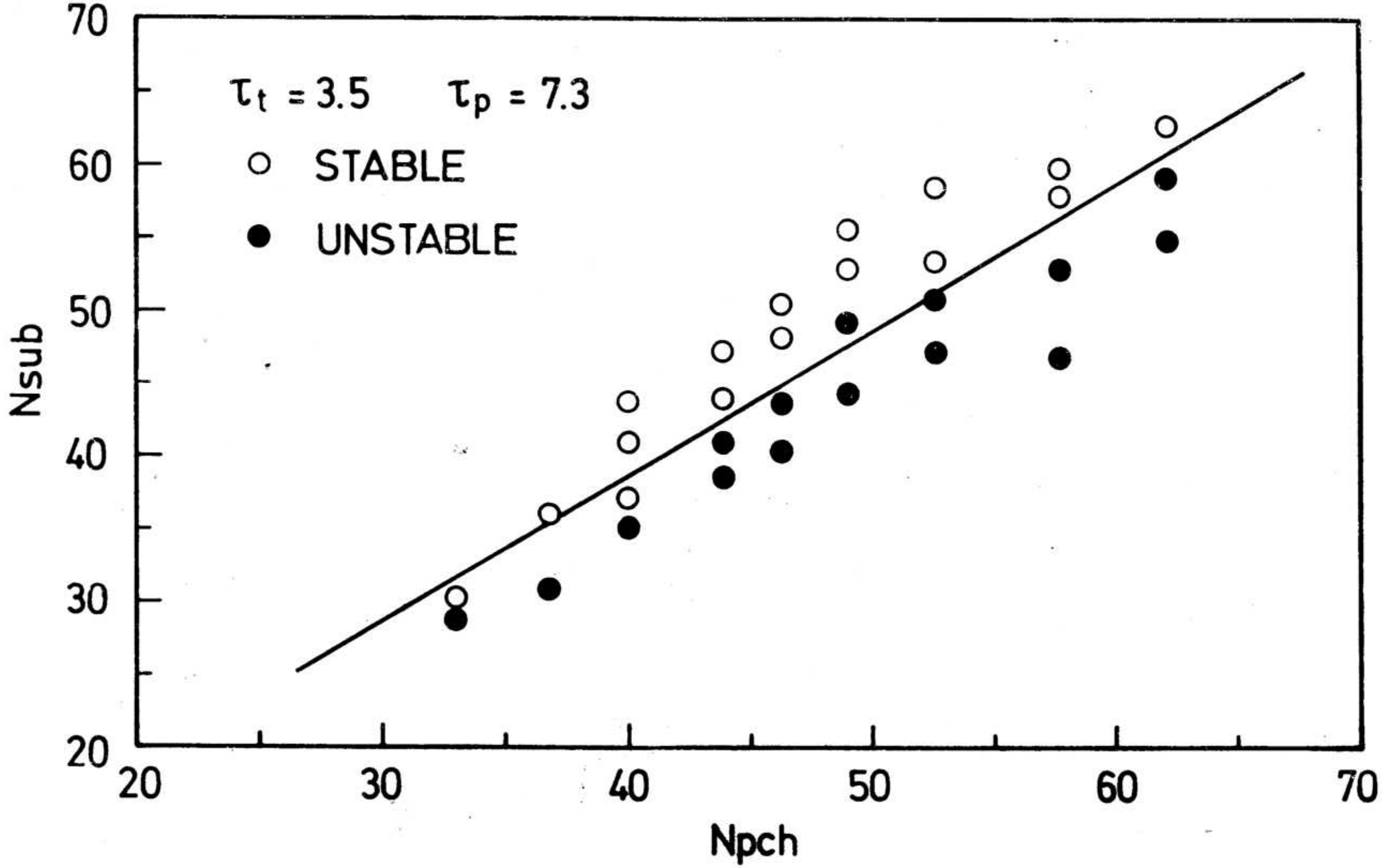
STABLE
UNSTABLE
Nsub
80
70
60
50
40
30
40
45
50
55
60
65
70
Npch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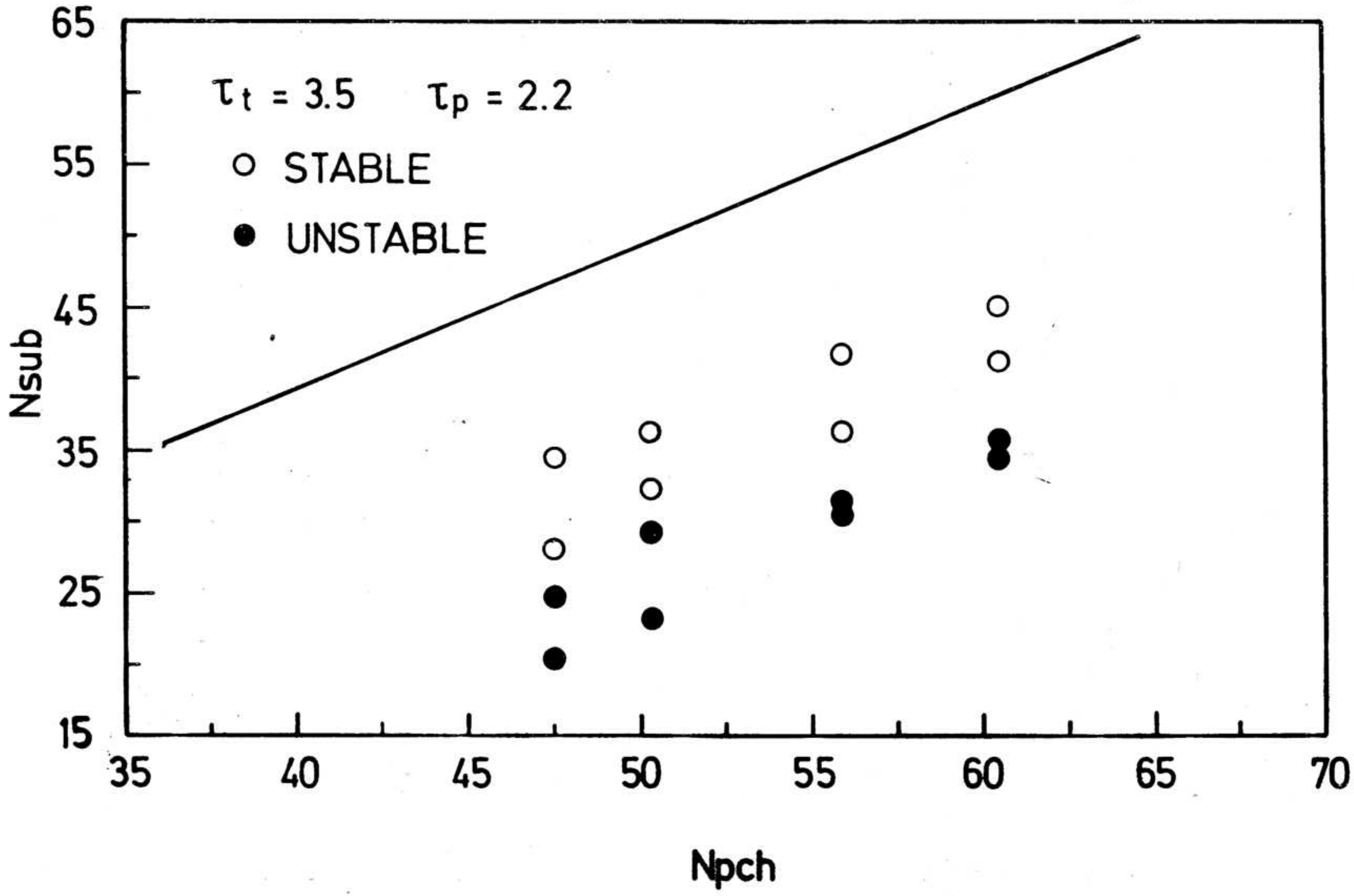
STABLE
UNSTABLE
Nsub
Npch
20
30
40
50
60
70



τt = 3.5 τp = 2.2
STABLE
UNSTABLE
Nsub
Npch
65
55
45
35
25
15
35
40
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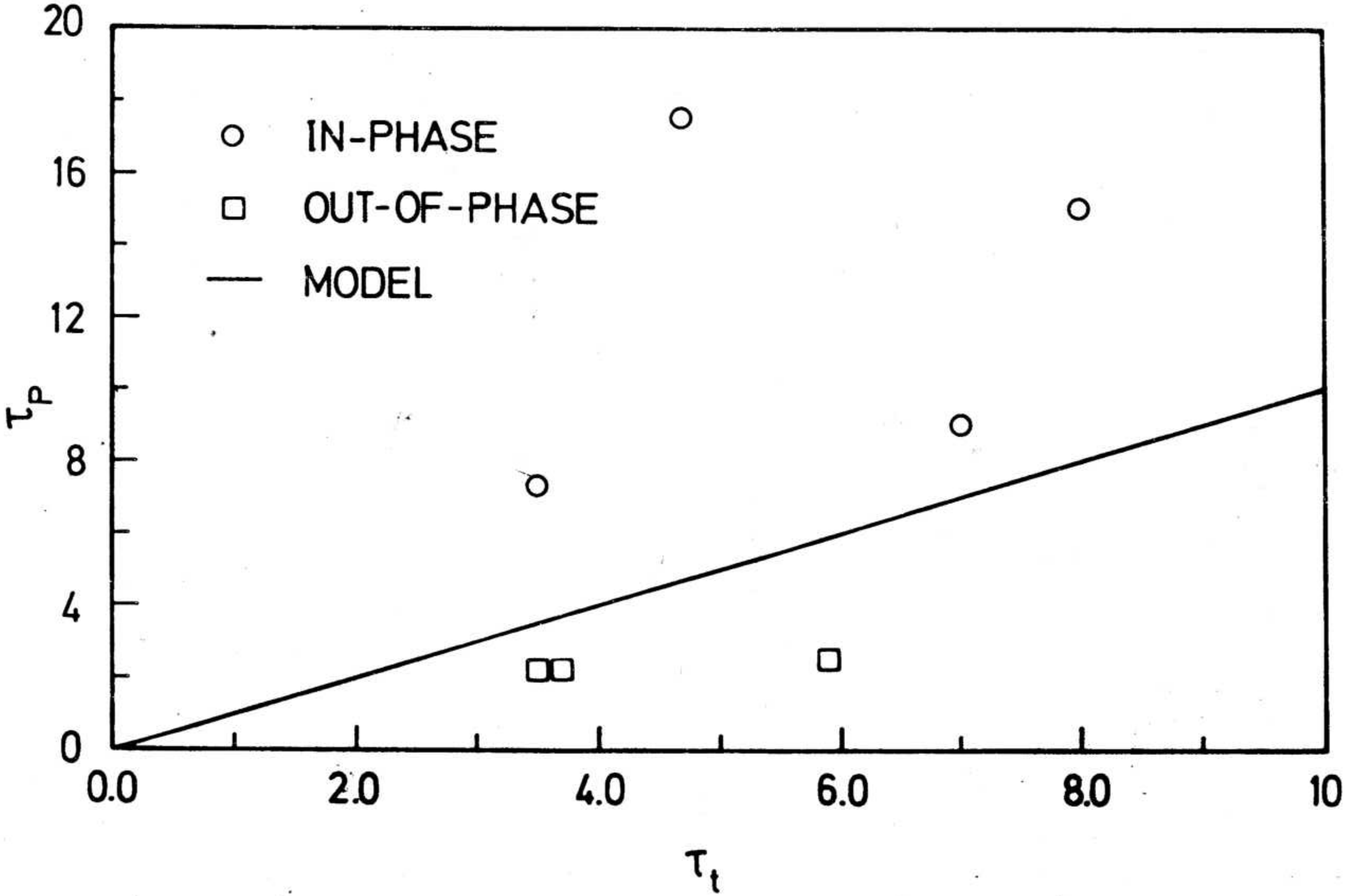
50
55
60
65
70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16
12
8
4
0
0.0
2.0
4.0
6.0
8.0
10
τ_P
τ_t
IN-PHASE
OUT-OF-PHASE
MODEL