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THERMALLY INDUCED OSCILLATORY TWO-PHASE FLOW IN A MINI-CHANNEL: TOWARDS UNDERSTANDING PULSATING HEAT PIPES

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ABSTRACT

Research on Pulsating Heat Pipes (PHP) has received substantial attention in the recent past, due to its unique operating characteristics and potential applications in many passive heat transport situations. Reliable design tools can only be formulated if the nuances of its operating principles are well understood; at present, this is rather insufficient for framing comprehensive models. In this context, this paper reports experimental data on self-sustained thermally driven oscillations in a 2.0 mm ID capillary tube sub-system, consisting of only one vapor slug and one liquid plug ('unit-cell'). Understanding such a sub-system/'unit-cell' is vital, as it represents a primary unit of a multi-turn PHP. Experiments have been performed with two fluids, i.e. Pentane (BP = 36.1ºC) and Methanol (BP = 64.7ºC) at different evaporator (40ºC to 65ºC) and condenser temperatures (-5ºC to 15ºC) respectively. High speed videography and spectrum analysis reveals that self-sustained thermally driven flow oscillations are observed for both fluids, albeit the dominant periodicity is different. Oscillation frequencies vary from 1.5 Hz to 4.2 Hz approximately, depending on the fluid, operating pressure and temperature. Increasing the difference of temperature between the evaporator and condenser sections leads to enhanced driving force for creating flow oscillations. The resulting phase velocities cause interfacial instabilities, resulting in the formation of secondary bubbles which break-off from the main meniscus. Results of this study can be compared to numerical models and will be useful to understand the physics of multi-turn PHPs.

Keywords: Pulsating heat pipe, Taylor bubbles, Oscillating slug flow, interface instability

INTRODUCTION

A Pulsating Heat Pipe (PHP) utilizes self-excited thermally driven two-phase flow oscillations for enhanced passive heat transfer. It is also referred to as an Oscillating Heat Pipe (OHP). This device has attracted considerable research in recent past due to its simplicity, ease of manufacture and favorable operating conditions under specified boundary conditions, as compared to other conventional heat pipes. The transport mechanism of this 'simple' device also poses an excellent opportunity to understand its complex internal two-phase thermo-hydrodynamics [1-5].

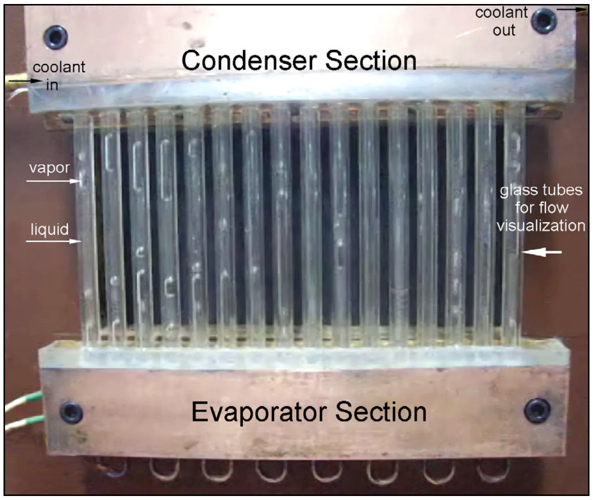

Fig. 1. Photograph of a multi-turn closed-loop PHP which is operating with ethanol as the working fluid. Internal diameter of the capillary tube is 2.1 mm [6].

A PHP is made of a simple meandering capillary tube which is evacuated and partially filled with a suitable working fluid. The device can be designed in at least three ways, namely: (i) open loop system, (ii) closed loop system and (iii) closed loop with additional flow control check valve(s). The closed loop system allows flow circulation while there is no such possibility in the open loop configuration.

Fig. 1 shows the photograph of a typical laboratory scale multi-turn PHP flow visualization setup [6]. Tube diameter should be sufficiently small so that slug flow is maintained inside it. Surface tension forces dominate gravitational forces in this condition. Maximum allowable diameter of the capillary tube is $\leq\ 2\left[\sigma/(\rho_l-\rho_v)g\right]^{1/2}$. Once filled, the working fluid and its vapor get distributed throughout the tube forming liquid slugs and vapor bubbles, due to the dominance of surface tension. When the evaporator section is heated, liquid plugs therein evaporate resulting in a rise in the local vapor pressure. This pushes the liquid plugs towards the condenser section by the action of vapor bubbles, which act as pumps. Thus, a self-sustained thermally driven (passive) oscillating flow develops inside the PHP capillary tube[1].

After the invention of this device by Akachi [1] in the early 90s, many investigators have tried to study this system, experimentally and numerically. Detailed review articles by Vasiliev [3], Zhang and Faghri [2], Khandekar et al. [5] give information about the present state of understanding and unresolved issues which need to be further explored. These include (but not limited to):

(i) There is no comprehensive mathematical model to predict the PHP thermal performance for a given boundary condition.

(ii) The understanding of heat transfer and pressure drop under self-excited thermally driven oscillating two-phase flow inside capillary tubes is rather incomplete. The transport phenomena in the unit-cell need to be resolved to predict global heat transfer parameters.

(iii) Multiple liquid-vapor unit-cells also interact with each other mutually; merger and coalescence of liquid slugs, breakage of Taylor bubbles under the impact of inertia and surface tension, nucleation inside liquid slugs, confined bubble formation, instabilities, condensation on liquid films, capillary waves, etc. are additional complexities in formulating PHP predictive tools.

Shafii et al. [7] thoroughly investigated both unlooped and looped PHPs numerically for different diameters, charging ratios and operating temperatures. These simple models, along with experimental studies and arguments thereof, suggest that the heat transfer in both types of PHPs is primarily due to exchange of sensible heat rather than by latent heat. It should be clarified here that while bulk of the heat transfer is due to the sensible heat carried by the liquid plugs, latent heat of the fluid is still a very important parameter as the efficacy of the bubble pumping action depends on it. Existence of the self-sustained thermally driven oscillations in PHPs is confirmed by different researchers [8-11]. Experiments by Charoensawan et al. [11] and Yang et al. [12] at different orientations showed that gravity does not have significant effect on the performance of the PHPs, especially in the bottom heating mode. However, Lips et al. [13] showed that for the same overall thermal performance, the leading mechanisms depend on the orientation, fluid nature and tube diameter. The relative importance of nucleation of bubbles and thin film evaporation on the heat transfer and fluid circulation can vary from one situation to the other. Natural oscillating frequencies in the range 0.1-5 Hz have been reported in such systems, depending on the boundary conditions [14].

In the simplest available mathematical model of PHP (a U-shaped miniature tube) with a single liquid plug or a vapor bubble (Zhang and Faghri [15], Dobson [16]), the vapor-phase is considered as an ideal gas. The fact that thin film evaporation causes high amplitude pressure fluctuations and that there exists a local two-phase equilibrium at the meniscus, has been neglected in the above mentioned simple models. Although thin film evaporation was taken into account by Dobson [16], interface saturation condition was neglected. Later, Zhang and Faghri [15] have taken this into account so that interface is near saturation. Recent modeling approach by Das et al. [17] includes the variable liquid film length and saturation condition at the liquid-vapor interface. Their results show good agreement with an experiment similar to that presented in this paper.

Present paper deals with the experimental results of thermally induced oscillations in a two-phase system consisting of a single vapor bubble and a liquid plug confined in a capillary tube of circular cross section (ID = 2.0mm). Two different working fluids, i.e. pentane and methanol, have been chosen for the experimental study, the details of which are explained next.

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[1] For brevity, many details of the PHP operating characteristics and thermo-fluidic behavior are not given here. Interested readers may refer to [1-6].

NOMENCLATURE

g	acceleration due to gravity, m·s^{-2}
p	pressure inside the capillary tube, Pa
T	temperature, ^{o}C
x	interface position measured from evaporator end, m

Greek symbols

σ	surface tension of the working fluid, N·m^{-1}
ρ	density, kg·m^{3}

Abbreviations

BP	Boiling Point
PHP	Pulsating Heat Pipe
ID	Internal Diameter

Subscripts

c	condenser
e	evaporator
l	liquid
r	reservoir
v	vapor

EXPERIMENTAL DETAILS

Fig. 2 shows the schematic diagram of the experimental set up. This system represents the simplest version of a multi-turn PHP, as shown in Fig. 1. The setup consisted of a capillary tube of ID = 2 mm connected between two reservoirs. This tube was heated at one end (evaporator section length = 15 cm; copper) and cooled at the other end (condenser section length = 25 cm; glass) by a transparent glass heat exchanger, as shown in Fig. 2. The latter served the purpose of flow visualization. The condenser was supplied by a constant temperature coolant. There was a small adiabatic section (length = 1 cm; glass) between the evaporator and condenser sections. Such a system, when subjected to a temperature difference in the evaporator and condenser section, could develop instabilities that led to thermally driven meniscus oscillations. The oscillations in the system (i.e., its instability) appeared when the difference between the temperatures T_e and T_c exceeded a threshold value.

An absolute pressure sensor (supplied by M/s KISTLER®, piezo-resistive sensor type 4005B, operating range of 0-20 bar, calibrated in the pressure range 0-3 bar with an accuracy of 2 mbar) was connected to one end of the evaporator. Another tube which came out of the evaporator end (at 0.7 cm from the end of the evaporator) was connected to a reservoir at vacuum, with an isolation valve in between. This tube connected with the vacuum reservoir served two purposes. It helped to remove any non-condensable gases present in the capillary tube before charging the device. Second, it helped to control the position of the liquid–vapor meniscus in the beginning of the experiment. Temperature of the evaporator was computer monitored with an accuracy of ±0.5°C.

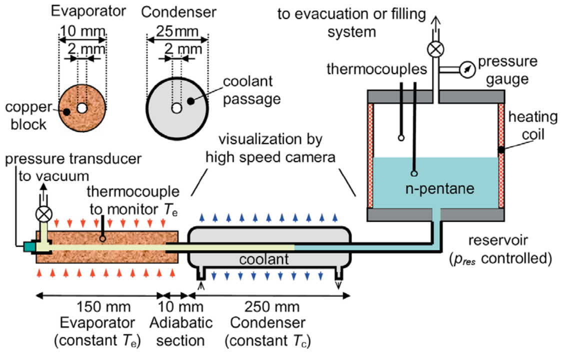


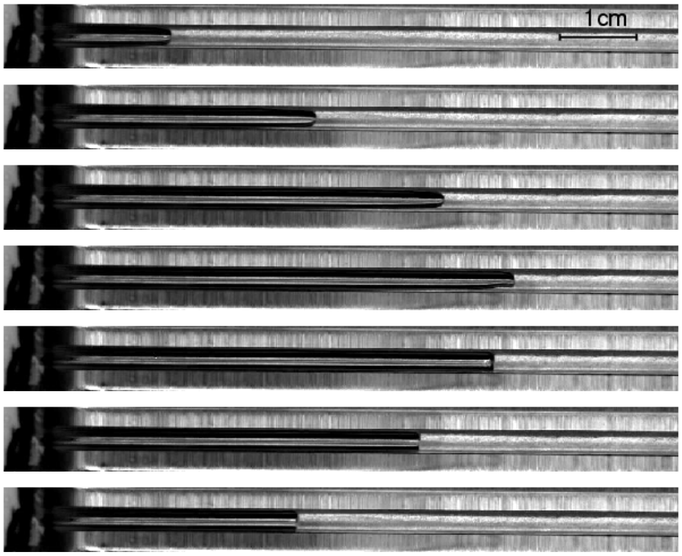
Fig. 2. Schematic diagram of the experimental set-up [16].

The condenser was a transparent water heat exchanger made of glass. Coolant water flow rate was constant and the temperature was controlled by means of a thermostatic bath in order to get a given constant working temperature. One end of this condenser glass capillary tube was connected to the evaporator and the other end was connected to a reservoir filled with saturated working fluid.

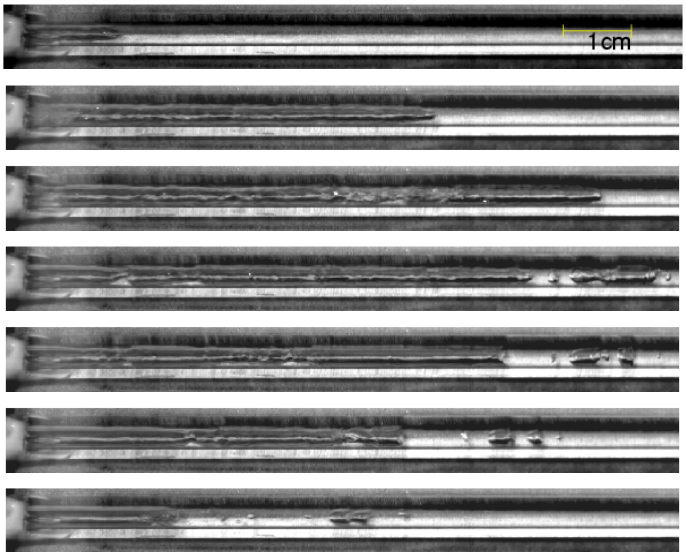
A heating coil was wound around this reservoir to fix its temperature, and thus experiments at different pressures could be performed. Reservoir pressure (i.e., system pressure) had significant influence on the oscillations of the vapor bubble. Before the experiments, the system was completely evacuated ($<10^{-4}$ Pa) to remove the non-condensable gases. Reservoir was then filled with the working fluid (pentane or methanol). Pressure gauge and thermocouple readings at equilibrium were used for cross checking the presence of pure vapor and liquid, i.e., to make sure that no non-condensable gases were present. Visualization was performed by a high speed camera (Fastcam-1024PCI) located over the condenser section; oscillations of the liquid-vapor meniscus and the vapor pressure were observed. Amplitude of oscillation was calculated from the acquired video images. Dominant frequency of oscillations was determined from the spectrum of the temporal pressure sensor data.

RESULTS AND DISCUSSIONS

We have performed experiments with two working fluids of different boiling points (pentane with boiling point of 36.1ºC and methanol with boiling point of 64.7ºC) and different latent heats to study the effect of those parameters on the thermal performance. Tests have been conducted for different ranges of reservoir pressure (p_r = 600 to 1100 mbar for pentane and 375 mbar for methanol), evaporator temperature (T_e = 40°C to 65°C) and condenser temperature (T_c = -5°C to 15°C). Experimental results, both with pentane and methanol, show the existence of self-sustained thermally driven oscillations in the capillary tube. At small condenser temperatures and moderate evaporator temperatures, the meniscus does not move out of the condenser. At high evaporator temperature, the vapor pressure is so high that interface of liquid and vapor goes out of the condenser section and sometimes it can also reach the storage reservoir containing the working fluid.



(a) Δt = 0.02 s



(b) Δt = 0.0133 s

Fig. 3. Flow visualization in the condenser section (liquid pentane on right-hand side (lighter part), vapor on left hand-side (dark part)) shows the meniscus position for a typical cycle using pentane (a) at T_e = 45°C, T_c = 10°C, $p_r = 9\times10^4$ Pa and, (b) at T_e = 57.5°C, T_c = -5°C, $p_r = 8.5\times10^4$ Pa.

Fig. 3 shows the flow visualization in the condenser section for pentane at low (45ºC) and moderately high (57.5ºC) evaporator temperatures, respectively. The time period between each snap-shot for the two cases is 0.02 and 0.0133s, respectively. At low evaporator temperature, velocity of the interface is small (Fig. 3-a); it increases when the evaporator temperature becomes high, thereby increasing the driving temperature difference between the evaporator and condenser. High velocity and condensation on the moving liquid film cause instability at the film interface. The oscillation amplitude also increases. When the condensation rates are high, secondary bubbles are formed, as seen in Fig. 3-b. It can occur during the movement towards or away from the evaporator as a result of pinching of the interface resulting in the formation of multiple bubbles. Unstable liquid film bulges towards central axis of the tube and coalesces with the bulged liquid film from the opposite wall. Often, the secondary bubbles were seen to quickly disappear by merging into the bigger vapor bubble. In a real operating PHP, multiple bubbles are formed by such instabilities (Fig. 1), which is similar as shown in Fig. 3-b. When secondary bubbles are formed, interface gets relocated.

Displacement plot for pentane (interface position x, measured from the evaporator end) in Fig. 4-a shows smooth variation for low evaporator temperature; in other experiments at higher evaporator temperature, the time-evolution of the meniscus location was observed to exhibit kinks because of the occurrence of interface instabilities. Fig. 4-b shows the pressure variation corresponding to the visualization shown in Fig. 3. Pressure amplitudes are about 1×10^4 Pa and 6×10^4 Pa respectively. Unlike lower evaporator temperature case, pressure curve is steeper in expansion phase than in compression. At high amplitude, oscillating liquid film enters deep into the evaporator and more liquid evaporates giving a large pressure rise in short time.

Fig. 5 shows the pressure variation in the tube for pentane and methanol at reservoir pressure of 8.5×10^4 Pa and 3.75×10^4 Pa respectively. Pressure in the tube is normalized with the reservoir pressure. Pentane shows a periodic variation. For methanol, intermittency is observed in the pressure curve. Fluctuation amplitude is less in case of methanol than in pentane. Latent heat of evaporation is nearly three times more for methanol, which requires more heat to evaporate equal amount of it, than pentane. In the present experiments, sometimes external disturbances (for example, tapping the setup with a mild mechanical jerk) were needed to commence oscillations, when the temperature difference between the evaporator and the condenser were low. This suggests the lack of required driving potential to overcome the necessary frictional resistances. Fig. 6 shows the frequency spectrum for a typical case, highlighting the dominant frequency of oscillation ~ 3.1 Hz. Fig. 7 shows the experimentally measured dominant frequency from all the experiments for methanol (124 experiments) and pentane (64 experiments) for different (T_e-T_c). There is a general trend of increase in frequency with the driving temperature difference between the evaporator and condenser. For a given temperature difference the scatter of the frequency data is realistic. They are obtained from the experiments with different reservoir pressure. For methanol, frequency variation is from 1.47 to 3.36 Hz and for pentane it is between 1.69 to 4.14 Hz. These range of dominant frequency values are inline with those reported by [14]. More systematic studies are required to discern the explicit parametric dependence of oscillating frequencies and threshold of instabilities in a pulsating heat pipe, as a function of the thermo-physical properties of the working fluid.

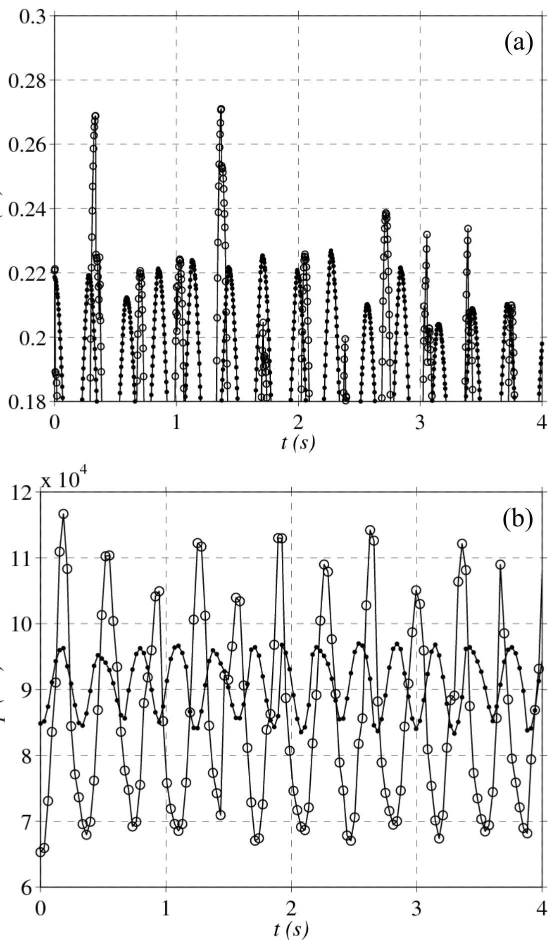


Fig. 4. (a) Displacement of the interface, and, (b) Pressure distribution for the case of pentane. Symbol • indicate the case when T_e = 45°C, T_c = 10°C and $p_r = 9\times10^4$ Pa; Symbol o indicates the case when T_e = 57.5°C, T_c = -5°C, $p_r = 8.5\times10^4$ Pa. These two cases correspond to the visualization results displayed in Fig. 3.

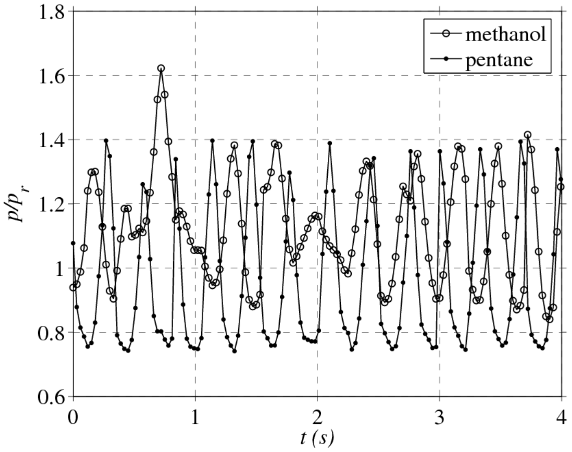


Fig. 5. Normalized variation of the vapor pressure in the tube for methanol (T_e = 65°C, T_c = -5°C, $p_r = 3.75\times10^4$ Pa) and pentane (T_e = 64°C, T_c = 0°C, $p_r = 8.5\times10^4$ Pa).

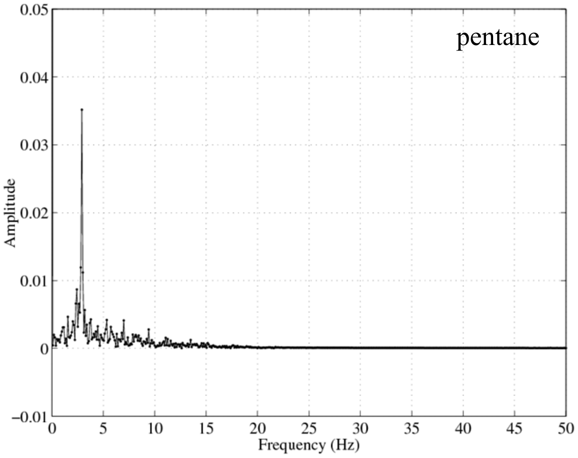


Fig. 6. Frequency spectrum for the case with T_e = 57.5°C, T_c = -5°C, $p_r = 8.5\times10^4$ Pa as shown in Fig. 4 shows the dominant frequency.

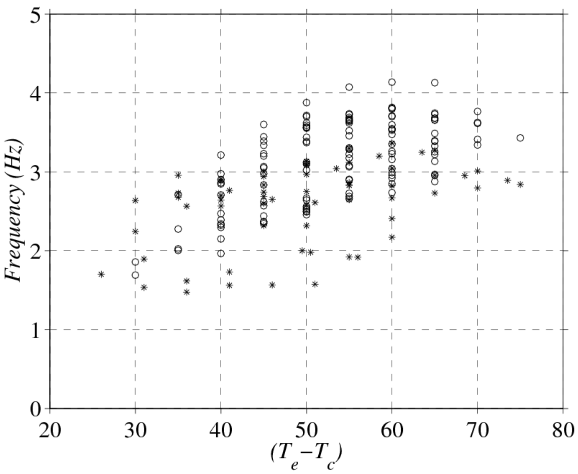


Fig. 7. Most dominant frequency, as measured from the raw data obtained by the pressure transducer, for all experiments conducted. Symbols o and * represent pentane and methanol, respectively.

SUMMARY AND CONCLUSIONS

Experimental results of a sub-system of a PHP, consisting of a single vapor bubble and a single liquid slug (unit-cell), operated with two fluids of different latent heat and boiling points respectively, clearly showed that flow oscillations exist even with a very small temperature difference between the evaporator and the condenser. When the latent heat of the working fluid is large, frequency of oscillations show occasional intermittency wherein smooth oscillations are not continuously observed. At high evaporator temperature and low condenser temperature, the oscillation is quasi-periodic for pentane; when this difference in temperature is small, the oscillations are only weakly periodic. Flow visualization results showed that when the oscillation amplitude is high, instability of the liquid film in the condenser can lead to the formation of secondary bubble(s) and thus the main interface gets relocated.

While the dominant frequency of oscillations is somewhat different (higher for pentane than methanol), the order of magnitude is the same and is inline with similar studies by other research groups. Typical range of dominant frequencies lies in the range of 1.5 to 4 Hz. It is recommended that more systematic studies on such simple-subsystems, representing the primary 'unit-cell' of a PHP device, i.e., single vapor bubble and liquid plug should be done so as to better delineate the underlying physics of the multi-turn PHP system.

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