

JoVE: Science Education

Frost Boss
--Manuscript Draft--

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Overview

Goal:

Our goal is to validate or invalidate the Spin and Chill claims and explain our observed results using the fundamentals of heat transfer and fluid flow.

You and your friends are traveling and stop at a store to buy some soft drinks. Unfortunately, the store only has room temperature soft drinks and bags of ice. But you notice a *Spin and Chill* sitting on a shelf. The *Spin and Chill* claims it will chill your warm 12 oz. beverage to 38F in a mere 2 minutes when it would take a refrigerator some 240 minutes and an ice chest 40 minutes. The *Spin and Chill* also claims this is accomplished by its cooler “gently” spinning at 500 rpm which creates little or no foaming. Will the *Spin and Chill* cool the beverage sufficiently for you to have a nice cold drink within minutes?

Comparable Technology:

The *Spin and Chill* makes use of transient heat conduction and convective heat transfer. By spinning, warm liquid from the middle of the vessel moves to the outside to contact the colder surface, and energy moves from the warm liquid to the cold surface in the form of heat. This continues until the entire vessel has been cooled. Refrigeration makes use of a similar process¹. In refrigeration, refrigerant cycles through the system, and undergoes a reduction in pressure¹. In response, the temperature of the refrigerant severely decreases to below the temperature of the space being cooled¹. This temperature difference results in heat moving naturally from the warmer space to the cooler refrigerant, where it is taken in, later emitted, and the process repeats itself¹.

Procedure:

This experiment is designed to assess the ability of spinning a vessel to cool a soft drink at record speeds. The *Spin and Chill* is designed to invalidate the use of an ice chest, in favor of chilling drinks quickly and individually. It will be tested in multiple rounds of experimentation, each designed to test it in different ways. Round 1 will examine the *Spin and Chill* using a lumped parameter model. Round 2 will examine the *Spin and Chill* using the transient heat conduction model in long cylinders. Round 3 will compare previous *Spin and Chill* experimental results from Round 1 with results and correlations found when varying the RPM of the device.

Principles

The Spin and Chill is analogous to the cooling of a batch vessel and somewhat analogous to the cooling of a fluid flowing in a pipe. In a batch vessel we have an agitator with known

properties and in a pipe problem we know the average fluid velocity. Theory and correlations are available to predict heat transfer coefficient (h) values. Heat flow in the *Spin and Chill* will be controlled by resistances. We want to focus on two limiting cases.

Case one, tested by round one and round three, utilizes a lumped parameter analysis. A lumped parameter analysis reduces a thermal system to a number of discrete “lumps”, where the temperature difference in each lump is considered negligible.

$$\frac{T(t) - T_{\infty}}{T_i - T_{\infty}} = \exp\left(-\frac{h A_s t}{\rho C_p V}\right)$$

Where T is temperature, h is heat transfer coefficient, A is area, t is run time, ρ is density, C_p is capacity, and V is volume.

Heat flow from the water in the can to the ice would involve an internal resistance, a wall resistance, and an external resistance (Figure 1). For case one to be applicable, both the water in the can and the ice must be well mixed. The problem is then simplified to a one-dimensional heat transfer problem.

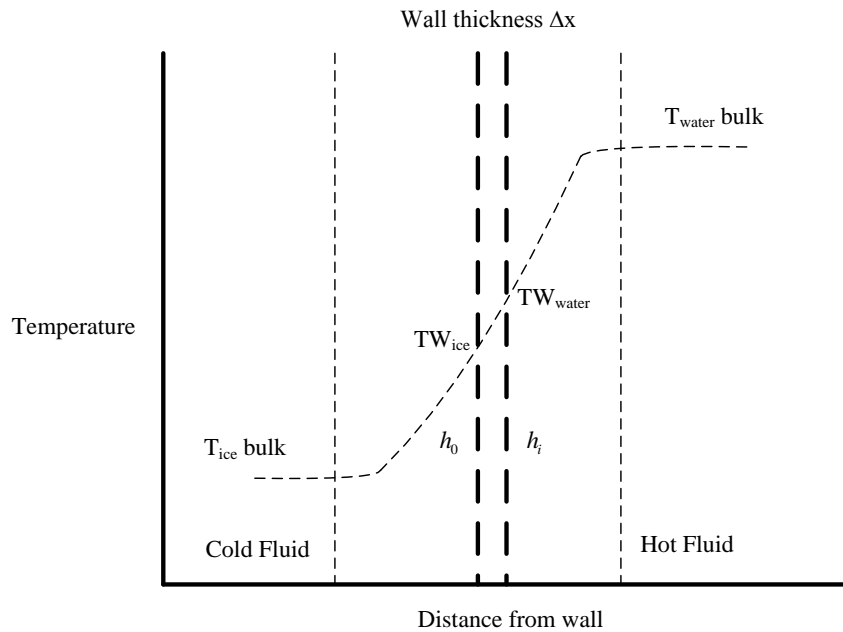


Figure 1: A schematic of temperature conditions for case one.

For case one, the wall is very thin and the wall resistance can be neglected. Here then heat transfer would be controlled mainly by the internal resistance. This will lead us to the lumped parameter analysis, which will allow determination of the internal resistance.

The Biot number is an index of the ratio of heat transfer resistances inside and outside a membrane.

$$Bi = Lh/k$$

Where Bi is the Biot number, L is the characteristic length (volume divided by surface area), h is the heat transfer coefficient, and k is the thermal conductivity. This number is used to compare heat transfer resistances between different bodies,

Case two, tested by the round two experiment, utilizes a one-dimensional transient heat conduction analysis.

$$\tau = \frac{\alpha t}{r_0^2} = \frac{\left(\frac{0.344 \frac{Btu}{hr-ft-F}}{\left(62.34 \frac{lb}{ft^3} \right) \left(1 \frac{Btu}{lb-F} \right)} \right) \left(120 s \frac{hr}{3600 s} \right)}{\left(1.25 in \frac{ft}{12 in} \right)^2}$$

Where τ is the time constant, α is the thermal diffusivity, t is time, and r_0 is the initial radius. This formula is used to find thermal diffusivity, which consists of the thermal conductivity divided by the density and heat capacity.

We want to evaluate if the can contents can be taken as a “solid-body.” If the water is a true “solid body” the bulk water temperature will not be uniform temperature and heat flow from the water will be controlled by conduction. With time the temperature at the center line of the can will evolve (Figure 2). Heat flow from the water to the ice would involve conduction through the “solid” and an internal resistance.

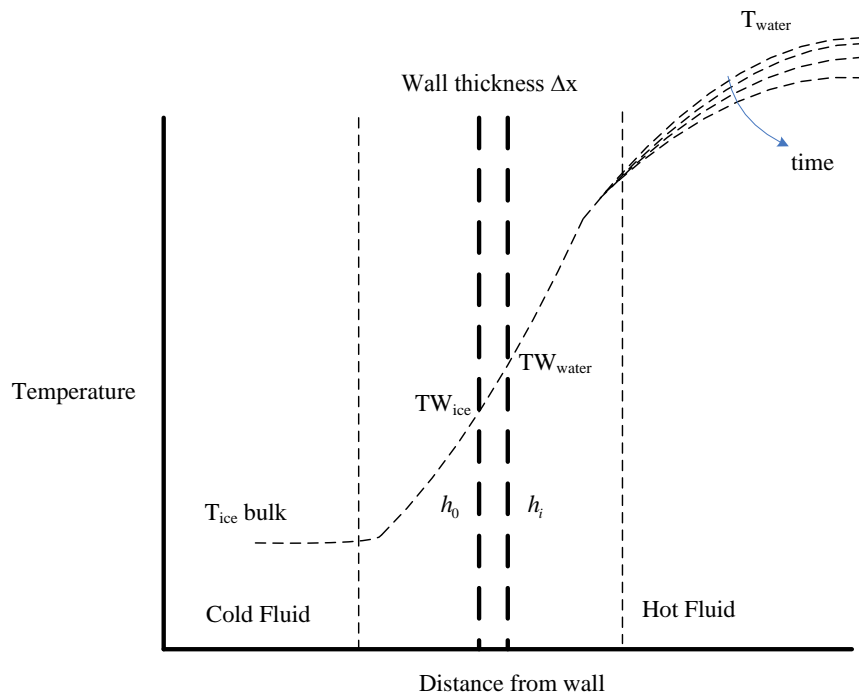


Figure 2: A schematic of temperature conditions for case two.

A difficulty with the Case II ice chest experiments in Round 2 is that water in the can will not be a “solid” as even without mixing, natural convection will be established due to the temperature gradients. But we can try to measure the center line temperature and determine an apparent internal resistance by assuming a long cylinder with heat conduction in the radial direction.

Procedure

Testing the Spin and Chill

1. Fill the aluminum soda can with room temperature water and then record the temperature.
2. Measure the total weight of the ice being used with the balance, enough to surround the Spin and Chill.
3. Seal the aluminum soda can using the provided plastic sealing lid and insert the assembly into the *Spin and Chill*.

4. Activate the *Spin and Chill*. It should run about two minutes at close to 500 rpm. Remove the aluminum soda can from the *Spin and Chill*.
5. Remove the plastic sealing lid, and record the final temperature of the water within the aluminum soda can. Record the amount of ice melted to water using either the graduated cylinder or the balance.

Round one experiment

1. Perform a reasonable number of replicates for the single run *Spin and Chill*. A reasonable number is 4 replicates, and the single runs will each start with the can at room temperature. Using the lumped parameter model, determine the single run heat transfer coefficient h (provide both Field (Btu/hr-ft²-F) and SI (W/m²-C) units for h). Also determine the system efficiency for each single run.
2. Run the *Spin and Chill* sequentially three times. Perform a reasonable number of replicates for the sequential *Spin and Chill* experiment. A reasonable number of replicates is about 4, with each replicate consisting of running the *Spin and Chill* three times in a row with the same can. Be sure to record the amount of ice melted and final temperature after each run. How close to 32 F do you think you can reach?
3. Using the lumped parameter model determine the heat transfer coefficient h (provide both Field and SI units for h) for each sequential experiment. Also determine the system efficiency for each sequential run.
4. Run the *Spin and Chill* with a warm can of soda. Pick the number of sequential runs you want to use to get to your desired drinking temperature. Be careful when you open the can – it may or may not foam. Be sure to record your final temperature so you can compare this temperature to your water results.
5. Are the values for efficiency all the same for the single runs and sequential runs experiments? Should the values for efficiency all be the same? Explain.
6. Are the values for h all the same for the single runs and sequential runs experiments? Should the values for h all be the same? Explain.
7. Determine and explain the Biot (Bi) number and its use in a lumped parameter analysis. Is it reasonable to say the contents of the can behave as a solid cylinder or solid lump and with the thermal conductivity k of water? Do you think a lumped parameter analysis is applicable in this experiment? Explain why or why not.

Round two experiment

1. Perform the same experiments as round one, with fewer replicates. Fewer replicates are needed because we have already examined the basic mechanism in round one.
2. Carefully set the can with water in an ice chest with ice. Cooling will take about 40 minutes.

Commented [HK1]: Same set of experiments but using an ice chest instead of the spin and chill, correct?

- Also in the same ice bath carefully set a similar sized aluminum cylinder (similar in size to the can and with a small hole drilled into the center line for temperature measurements). Every few minutes measure and record the temperature in the center of the can and the aluminum cylinder – be careful not to stir or disturb the can contents.
- Using data from Round 1 + your replicates for the same experiments use the lumped parameter model to determine the heat transfer coefficients h (provide both Field (Btu/hr-ft²-F) and SI (W/m²-C) units for h). Determine the efficiencies. Determine the Biot number.
- Using a “typical” calculated value for h from the lumped parameter analysis (from Round 1 data + your replicates) and appropriate system properties, determine the center line temperature for long cylinder. Explain what is happening here.
- Determine the heat transfer coefficient h (provide both Field and SI units for h) for both the can/water and aluminum cylinder. What is the long time requirement for these experiments? Explain the difference between this h value and the h value determined from the lumped parameter analysis from the working *Spin and Chill* in Round 1.

Commented [HK2]: In round two there is no spinning of the can is that correct? The can is just sitting in the ice bath?

Round three experiment

- Perform the same experiments as round one. Combine data with previous runs, and only replicate a few times, since we have already performed the replicate several times previously. Using the lumped parameter model determine the heat transfer coefficient h (provide both Field (Btu/hr-ft²-F) and SI (W/m²-C) units for h). Determine the efficiency and the Biot number.
- Perform a reasonable number of replicates for the single run *Spin and Chills* each at a different rpm. The run time should be ~ two minutes. Also try a few runs at different run times. You will want to reasonably span a few rpm to 500 rpm which is the expected rpm from *Spin and Chill*.
- Using the lumped parameter model (Section 4.1) determine the heat transfer coefficient h (provide both Field (Btu/hr-ft²-F) and SI (W/m²-C) units for h) for the different rpm and run times you have selected. Also determine the system efficiency for each run.
- Does the efficiency change with rpm and run time? Does the h value change with rpm and run time? Explain why or why not this happens.
- Plot h (or some form of h) on the y-axis as a function of something on the x-axis. Your choice for the y-axis and x-axis may be influenced by later discussion questions in this round.

Representative Results

Round One

Trial #	lbs of water	Initial Temp	Final Temp	ΔT (°F)	Ice Δm	Q_{ice}	Q_{water}	η	h Btu/hr-ft ² -F	h W/m ² -C
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		(°F)	(°F)		(lbs.)					
1	0.783	77	53.42	23.58	0.172	24.768	18.463	74.54	70.545	400.574
2	0.783	84.74	60.08	24.66	0.17	24.48	19.309	78.88	59.899	340.126
3	0.783	86	59.72	26.28	0.175	25.2	20.577	81.66	63.369	359.829
4	0.783	83.12	55.4	27.72	0.195	28.08	21.705	77.30	74.261	421.674
6	0.783	81.86	52.34	29.52	0.212	30.528	23.114	75.71	85.207	483.832
7	0.783	83.66	58.28	25.38	0.171	24.624	19.873	80.70	64.229	364.710
8	0.783	79.16	50.72	28.44	0.203	29.232	22.269	76.18	87.804	498.576
9	0.783	81.68	56.3	25.38	0.181	26.064	19.873	76.25	67.959	385.890
10	0.783	81.86	56.66	25.2	0.173	24.912	19.732	79.21	66.905	379.906
Avg.	0.783	82.12	55.88	26.24	0.18	26.43	20.55	77.73	70.454	400.057

Table 1: Single-run nominal temperature change from 82 F to 56 F in round 1.

Trial #	lbs of water	Initial Temp (°F)	Final Temp (°F)	ΔT (°F)	Ice Δm (lbs.)	Q_{ice}	Q_{water}	η	h Btu/hr-ft ² -F	h W/m ² -C
1a	0.783	80.78	53.6	27.18	0.176	25.344	21.282	83.97	77.414	439.582
1b	0.783	53.6	41.9	11.7	0.095	13.68	9.161	67.10	74.335	422.095
1c	0.783	41.9	38.3	3.6	0.038	5.472	2.819	51.77	43.223	245.430
2a	0.783	74.48	55.76	18.72	0.137	19.728	14.658	74.30	55.216	313.530
2b	0.783	55.76	43.34	12.42	0.088	12.672	9.725	76.90	70.477	400.188
2c	0.783	43.34	37.04	6.3	0.062	8.928	4.933	55.53	77.548	440.340
3a	0.783	71.42	49.28	22.14	0.141	20.304	17.336	85.38	78.374	445.030
3b	0.783	49.28	39.56	9.72	0.077	11.088	7.611	68.78	78.767	447.264
3c	0.783	39.56	35.96	3.6	0.046	6.624	2.819	42.77	61.836	351.122

Table 2: Three sequential runs with nominal temperature change of 75 to 53 F, 53 to 41 F, and 41 to 37 F in round 1.

The observed efficiency is not dependent on any limiting case or heat transfer mechanism. To calculate the efficiency, we first determine the energy into the ice and from the water. If the system were adiabatic (100% efficient), $Q_{water} + Q_{ice} = 0$. The efficiency is determined by dividing the absolute value of heat energy of the water (Q_{water}) by the heat energy of the ice (Q_{ice}) (Table 1). For the sequential runs, the efficiency (η) decreases from 78% to 71% to 50% as temperatures closer to 32 F are obtained (Table 2). The efficiency (η) drop with sequential runs is expected, since the efficiency of heat transfer is reduced when temperatures are closer to one another. The liquid inside the can is becoming closer in temperature to the ice outside, therefore the efficiency reduces. The Biot numbers were found to be around 10 for all the runs in round one. These heavily exceed the expected value of 0.1. The much larger value indicates much larger resistance outside the can than inside. But the Biot number is more accurately stated as the external resistance to heat flow divided by the internal resistance. Here larger numbers for h and k are indicative of less resistance or "greater" heat flow. A very large k would create a uniform temperature in that "k" phase. In our experiment the rotating can/vessel appears to create a well-mixed vessel. The lumped parameter analysis is perfectly applicable.

Round Two

$$T_{center} = (T_i - T_\infty) A_1 \exp(-\lambda^2 \tau) + T_\infty =$$

$$(77 - 32) 1.5677 \exp(-(2.1795)^2 (0.01695)) + 32 =$$

$$65.09 + 32 = 97.09 F$$

An initial calculation of the temperature of the center using the suggested parameters suggests an impossible violation of the second law of thermodynamics. However, the problem is this equation does not provide for a short time solution, only solutions over a longer term. Additional parameters must be added to satisfy shorter time periods.

We are considering heat transfer resistances in the water and aluminum as h and pure conduction, k . If the conduction is pure – as occurs in a solid body – then the observed h values should be the same for both systems. But for the water system some natural convection will occur and the h values are not expected to be the same in the two systems.

Round Three

The third series of tests varied RPM and run times. When varying RPM, it was found that the average temperature of the liquid inside the can was inversely proportional to the RPM. Greater RPM tests led to lower liquid temperatures, closer to the ideal temperature, while reduced RPM tests led to higher average temperatures. Faster RPM tests reduced the temperature of the liquid more successfully than the tests with lower RPM.

A similar relationship was found between run time and temperature at constant RPM. When the can was spun for a reduced amount of time, the average temperature was warmer than when the can was spun for the full amount of time. The relationship was found to be that an increase in run time leads to an increased change in temperature and an overall cooler temperature on average.

Summary

This experiment is designed to assess the ability of a spinning vessel to cool a soft drink at record speeds, the *Spin and Chills*. Round one examines the *Spin and Chill* using a lumped parameter model. Round two examines the *Spin and Chill* using the transient heat conduction model in long cylinders. Round three compares our *Spin and Chill* experimental results with results and correlations found in another research experiment. Theory and correlations are available to predict h values. Heat flow in the *Spin and Chill* will be controlled by resistances.

The efficiency drop found in sequential runs was expected. The Biot numbers were found to be around 10 for all the runs in round one. These heavily exceed the expected value of 0.1. The data collected calls into question the ability of the *Spin and Chill* to cool a warm can of soda to 38F in 2 minutes. However, with three sequential uses and a time period of about 6 minutes, the *Spin and Chill* can cool the soft drink to the desired temperature of 38F. While the initial claims were invalidated, the concept does provide an advanced cooling method that could be made more efficient with more testing in the future.

Applications

Commented [HK3]: Is it possible to present round three data in graph format. It is more visual and might help in discussion.

Commented [MC4R3]: Unfortunately we do not have exact data for this round of the experiment, so we could not include it in the report.

The lumped parameter model has been applied to a wide variety of fields. By use of a lumped parameter analysis, forensics labs can determine time of death of a human body². Forensic scientists treat the body as a lumped system². Previous research was conducted on cooling when considering factors such as body size and shape². Differential equations are then used with these known cooling factors to determine relative time of death².

Another use of the lumped parameter model is in the advancement of HVAC (heating, ventilation, and air conditioning) systems³. Heat load distribution can be computationally predicted with a lumped parameter model to maximize energy efficiency³. These models account for fluid transport, energy transport, thermodynamics, and psychrometrics³. By fitting HVAC systems to a lumped model, engineers can maximize their efficiency, reducing costs and energy usage, while increasing the effectiveness of the climate control system³.

Transient heat conduction modeling is important in a variety of engineering fields, including materials processing, power station engineering, and refrigeration. Heat exchangers are one common application of transient heat conduction⁴. These devices take energy from a hot stream and use it to heat a cooler one⁴. Shell and tube are the most common type of exchangers⁴. They are normally long cylinders, similar to the model used for this experiment, but much larger in scale⁴. Several tubes inside a larger cylinder shell contain one flowing liquid, while a separate one flows through the shell⁴. Flow can be in the same or different directions. Heat will flow from the hottest stream to the colder one⁴. These tools can be used in many industries, such as chemical manufacturing and oil refining, where they can be used to heat or cool chemicals or oil⁴.

Sources

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