



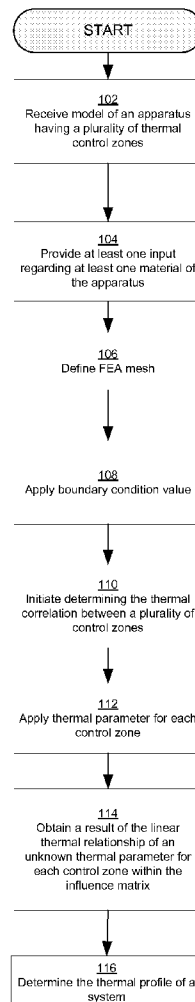
US 20080099569A1

(19) **United States**(12) **Patent Application Publication**
PLUMPTON et al.(10) **Pub. No.: US 2008/0099569 A1**(43) **Pub. Date: May 1, 2008**(54) **THERMAL ANALYSIS OF APPARATUS
HAVING MULTIPLE THERMAL CONTROL
ZONES****Publication Classification**(51) **Int. Cl.**
F24D 19/10 (2006.01)(52) **U.S. Cl.** **236/1 B**(75) Inventors: **James Osborne PLUMPTON**,
Enosburg Falls, VT (US); **Zakiul**
HAQUE, Essex, VT (US)(57) **ABSTRACT**

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**HUSKY INJECTION MOLDING SYSTEMS,
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CO/AMC INTELLECTUAL PROPERTY GRP
500 QUEEN ST. SOUTH
BOLTON, ON L7E 5S5(73) Assignee: **HUSKY INJECTION**
MOLDING SYSTEMS LTD.,
Bolton (CA)(21) Appl. No.: **11/554,899**(22) Filed: **Oct. 31, 2006**

Systems and methods for conducting thermal analysis in materials and devices having multiple thermal control zones are provided. Modern apparatuses, such as manifolds, generally have several thermal devices that introduce or remove heat at different rates from several different regions. Previous attempts to determine a thermal profile required constant guessing and an unknown number of simulations to arrive at an acceptable result. Further, since the number of simulations required is not known from the onset of the operation, the duration is unknown, which is often unsatisfactory to manufacturing personnel. Disclosed embodiments include the use of FEA to aid in designing and/or evaluating manifold systems. In one embodiment, finite element analysis is conducted to determine the heat flux caused upon other control zone by a thermal device in a specified control zone.



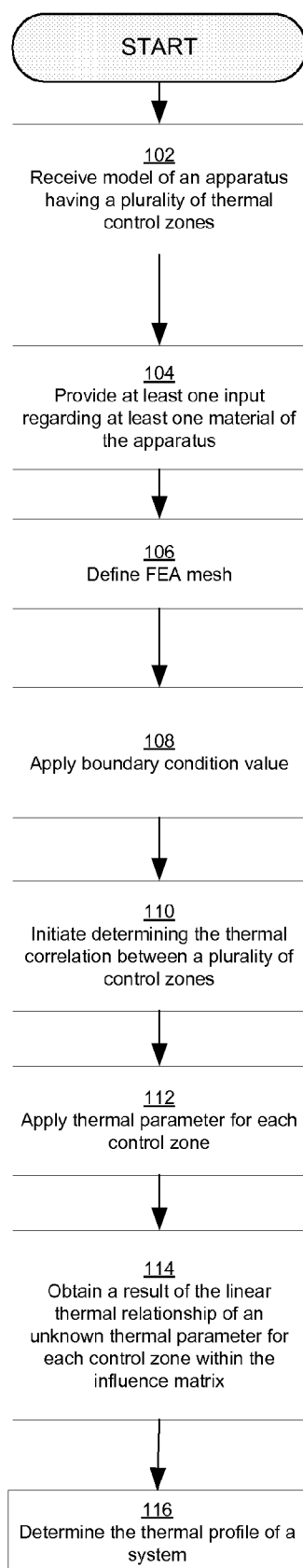
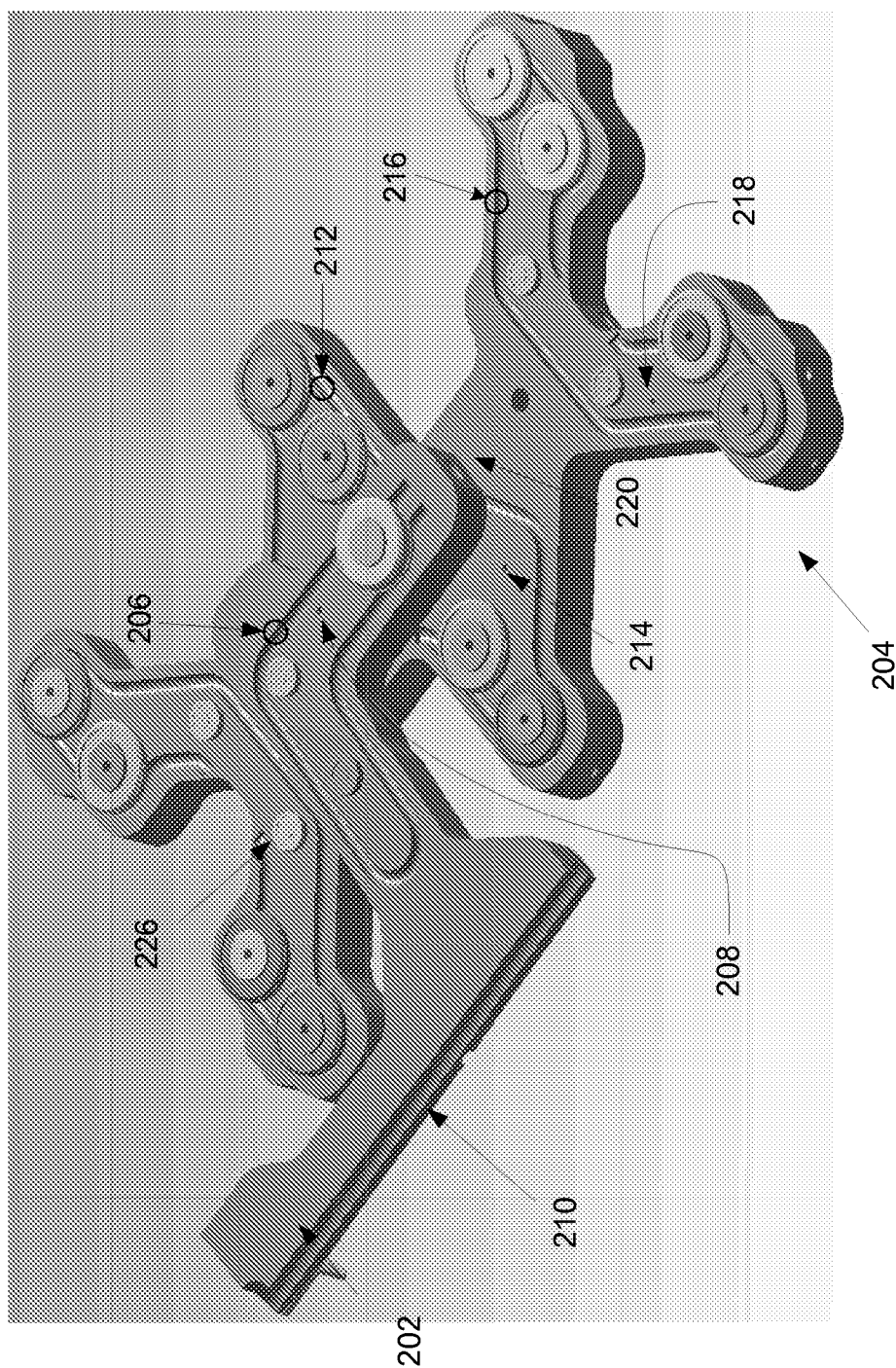


Figure 1

200



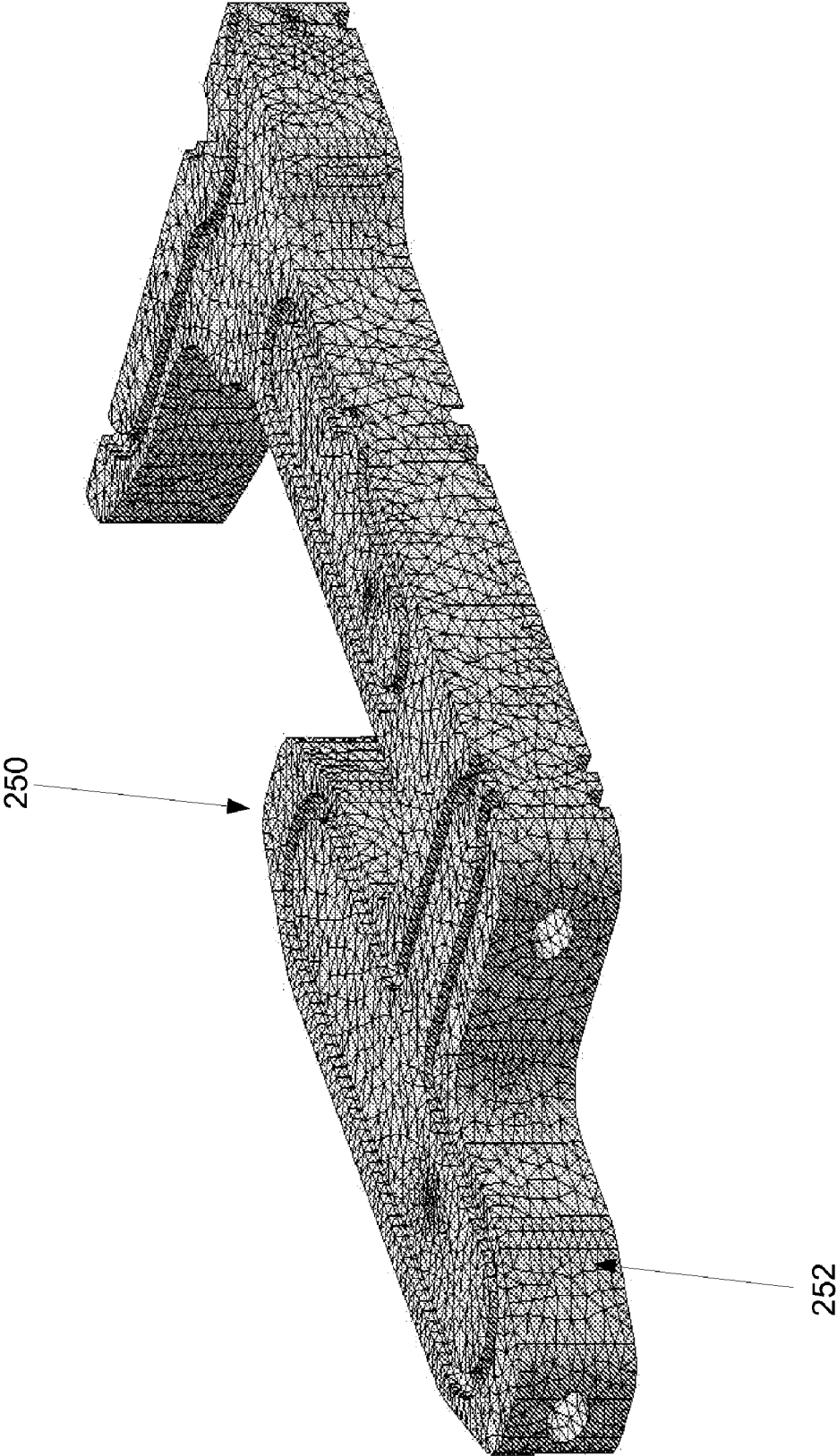


Figure 2b

300

Iteration 302	Htr_1 304	Htr_2 306	Htr_3 308	TC_1 316	TC_2 318	TC_3 320
1	q	0	0	T11	T21	T31
2	0	q	0	T12	T22	T32
3	0	0	q	T13	T23	T33

Figure 3a

Simulation	Heater_1 Heat flux W/mm ²	Heater_2 Heat flux W/mm ²	Heater_3 Heat flux W/mm ²	Simulation	TC_1 Temp °C	TC_2 Temp °C	TC_3 Temp °C
1	0.1	0.0	0.0	1	680	255	63
2	0.0	0.1	0.0	2	684	846	232
3	0.0	0.0	0.1	3	293	636	1049

Figure 3b

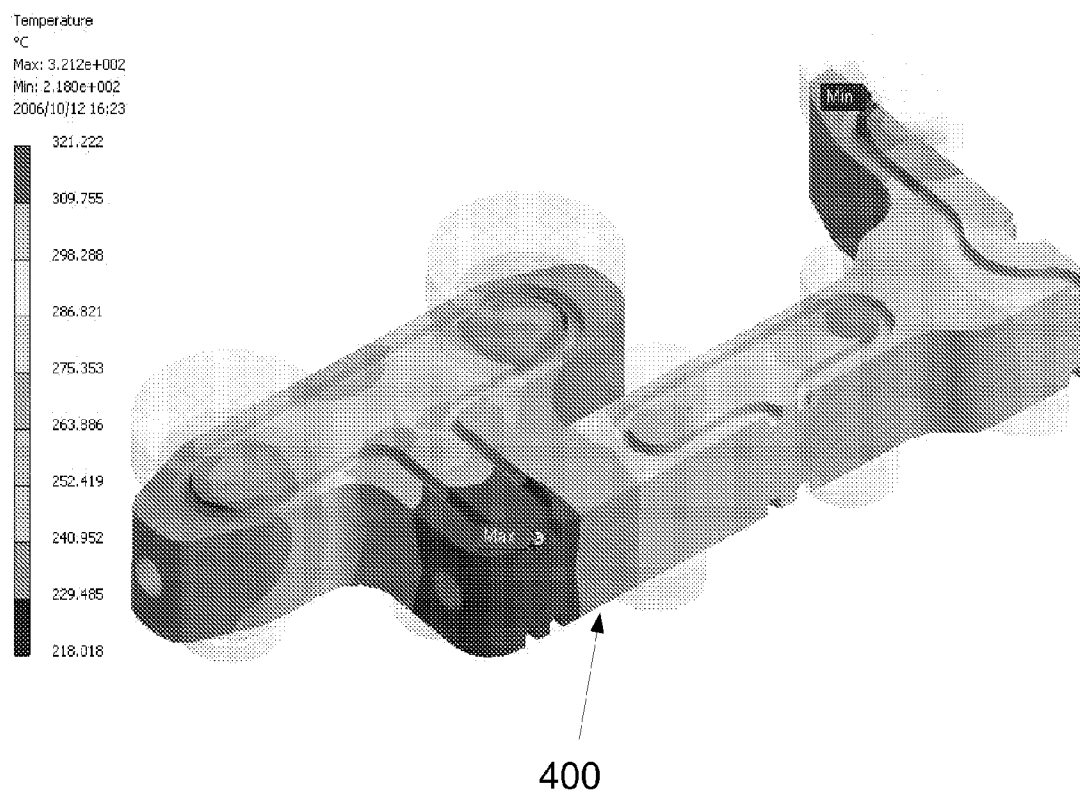


Figure 4

THERMAL ANALYSIS OF APPARATUS HAVING MULTIPLE THERMAL CONTROL ZONES

INTRODUCTION

[0001] This invention relates to systems, methods and devices for conducting thermal determinations of apparatus, such as design or analysis of apparatus or devices. More specifically, aspects of the invention are directed towards thermal design or analysis of apparatus or devices having multiple thermal control zones.

BACKGROUND

[0002] Industrial tools and other apparatus are often placed under high stress loads. The stress may be in the form of, for example, mechanical, frictional, and/or extreme thermal conditions. This is especially true of tools utilized in manufacturing products under high temperatures and pressures, such as tools for making injection molded plastic products. Such tools must not only be designed to withstand the thermal conditions, but also to remain within certain pre-defined operating thermal parameters for proper operation. For example, when injection molding resin or other materials to create plastic products, utilizing a temperature that is too high could result in "burning" the resin and/or improper formation of the desired product. Conversely, if a desired temperature is not reached, the resins may not properly flow or mix or otherwise perform suitably to form the desired end-product. The complex problem of properly designing apparatus such as industrial tools is compounded when the apparatus has multiple thermal zones, each comprising one or more thermal devices, such as heaters or coolers, that affect temperature in their own zone and that of other zones of the apparatus.

[0003] Modern apparatus, for example injection molding manifolds and the like, generally have more than one thermal device, each of which, as explained in more detail below, introduces or removes heat from the apparatus. Generally, each region or zone of the apparatus is in thermal communication with one or more other zones of the apparatus. Thus designing and analyzing the thermal properties or performance of such apparatus, including, for example, determining a thermal profile of the apparatus under usage conditions, requires recognition that each zone impacts the thermal properties or performance of one or more other zones. As one skilled in the art will readily appreciate, this is a complex and time consuming undertaking, especially with an apparatus having multiple thermal control zones, where each zone has a control associated with a thermal device whose thermal output affects the thermal properties or performance of one or more of the other control zones, each of which may, in turn, have a control and an associated thermal device that influences the thermal properties or performance of the first and/or other control zones of the apparatus.

[0004] Previous approaches used to determine a thermal profile of an apparatus included the use of an iterative process employing finite element analysis (FEA). Typically, in such prior approaches, a large number of calculation simulations are needed to approach an estimation of the thermal profile of the apparatus in operation. Such simulations require undesirably large amounts of computing and personnel time. Also unfortunately, such known iterative

processes require guessing or estimating the value of one or more variables and an unknown number of simulations to arrive at an acceptably accurate result. The required computational time for each successive simulation to be performed often precludes the computation of a fully satisfactory estimate of the thermal profile of the apparatus. Rather the process is often stopped or otherwise not conducted before a more precise and accurate result is obtained. Further, since the number of simulations required is not known from the onset of the operation, the duration is unknown, which is often unsatisfactory to manufacturing personnel. Where each of multiple zones of an apparatus has a thermal device whose thermal output indirectly affects the thermal properties of one or more of the other control zones, the synergistic complexity of the problem increases as the number of control zones increases.

[0005] Some or all of these and other shortcomings of traditional methods of determining a thermal profile of an apparatus having a plurality of thermal control zones are overcome according to various methods and systems encompassed in different embodiments of the invention. Additional objects or advantages of various embodiments of the invention will be apparent from the following disclosure.

SUMMARY

[0006] A first aspect of the invention is directed towards methods and systems implementing finite element analysis to aid in the determination, e.g., the design or analysis, of an apparatus having multiple thermal control zones. In certain exemplary embodiments the methods and systems are fixed-simulation methods and systems, as further disclosed below. In certain exemplary embodiments, the apparatus has multiple thermal control zones, each of which control zones has a control (also referred to here as a thermal controller) and an associated thermal device, such as a heater or cooler, whose thermal output directly affects the thermal performance or properties (e.g., the temperature) of that zone and also directly or indirectly affects the thermal properties of one or more of the other control zones of the apparatus. In certain exemplary embodiments, the apparatus to be designed or analyzed is a manifold for injection molding plastic or other material, wherein the manifold has multiple thermal control zones, each of which control zones has a control and an associated thermal device whose thermal output directly affects the temperature of that zone and indirectly affects the temperature of one or more of the other control zones of the manifold.

[0007] It will be understood by those skilled in the art, given the benefit of this disclosure, that the thermal device of any such zone of the apparatus may comprise operative components at one or more locations in the zone. In addition, the boundary between one thermal control zone and the next within an apparatus may in some instances be selected from amongst multiple (even infinite) suitable alternatives. As one skilled in the art will readily appreciate upon reading the disclosure herein, the term boundary does not signify a physical separation or boarder (although in select embodiments, the boundary will be defined by a physical structure). Rather, the boundary may be virtual and defined merely on non-physical features. In select embodiments, the apparatus is divided up into several symmetric portions. As used herein, the boundaries between control zones may be any line, collection of lines, plane or collection of planes defining at least a portion of border of a specific control zone.

[0008] Typically, but not necessarily in all embodiments disclosed here, a thermal zone of a multi-zone apparatus designed or analyzed by a finite element analysis method or system disclosed here is not controlled by the thermal controller of another zone other than indirectly, such as by the cross-boundary effect of the temperature of one zone on adjoining zones. It will be within the ability of those skilled in the art, given the benefit of this disclosure, to determine suitable zone boundaries.

[0009] In accordance with another aspect, certain systems and methods disclosed here employ a finite element analysis to determine, i.e., to design or to analyze the design of apparatus (i.e., within all or at least a portion of the body of the apparatus or of components of the apparatus) having multiple, independently controlled thermal control zones, wherein the temperature of at least one such zone during operation of the apparatus directly or indirectly affects the temperature of at least one other such zone. As the term is used here, zones are "independently controlled" if (i) the thermal device(s) within the zone are actuated (e.g., operated or energized) only in response (directly or indirectly) to signals generated by one or more temperature sensors within that zone and/or (ii) the thermal device(s) within the zone are not adapted to be actuated in response (directly or indirectly) to signals generated by any temperature sensor(s) within any other zone of the zone.

[0010] In certain exemplary embodiments finite element analysis is implemented to aid in the design or analysis of a manifold system, e.g., an injection molding manifold system, comprising one or more than one individual manifold. In certain embodiments, for example, fixed-simulation finite element analysis is conducted to determine the heat flux caused by actuation of a thermal device in a specified control zone of the manifold system upon one or more other control zones of the manifold system. In certain such embodiments, the thermal device of a control zone is a heater, such as but not limited to resistive heater. In certain exemplary embodiments the heater is operative to heat a liquid or other fluid in a channel extending in the manifold, including at least partially in the particular control zone in question. Yet in other embodiments, the heater is operative to maintain an elevated temperature of a liquid or other fluid in the manifold. As used herein, the term liquid may include any chemical, matter or material that may change shape as it travels through a passage, such as a channel. For example, the liquid may be fine or coarse, and at select temperatures be considered a semi-solid. The texture of the liquid may range from dense to soft and from runny to a paste-like consistency including slurries. Thus, in select embodiments, the liquid forms to the shape of the passage it is traveling within.

[0011] In certain exemplary embodiments the thermal device of a control zone is a cooler or chiller, e.g., a thermoelectric cooling device operative to remove heat from the zone in question. Other embodiments of the invention will be readily apparent to those of ordinary skill in the art, including, e.g., embodiments wherein finite element thermal analysis as disclosed here is used to determine other thermal parameters. As used here, the term thermal parameters is used to mean the thermal operating properties, thermal performance under normal operating conditions or under other conditions, thermal profile (temperature gradients or

the like) and/or other properties, characteristics, etc. of an injection molding manifold or other apparatus having multiple thermal control zones.

[0012] In accordance with another aspect, systems and methods comprise implementation of finite element thermal analysis to determine the thermal parameters of an apparatus having multiple control zones, and further comprises utilizing the results of such analysis, e.g., the thermal relationship between zones of the apparatus obtained from such finite element analysis to determine a thermal profile of the apparatus under defined conditions. In certain exemplary embodiments, the thermal profile graphically displays the temperature values obtained, e.g., by one or more graphical displays visible to a user. In further embodiments, the thermal profile may be utilized to further aid in the design of the apparatus, e.g., determining an initial design for the apparatus before it is constructed or determining an alteration of the existing design of the apparatus.

[0013] In accordance with another aspect of the invention, finite element analysis is utilized in a system or method to create an influence matrix suitable for use in determining the design of an apparatus, e.g., to aid in the confirmation of a thermal profile of an injection molding manifold or other apparatus having multiple control zones. In certain exemplary embodiments, one control zone may span over multiple components.

[0014] In certain exemplary embodiments finite element thermal analysis is employed to determine the thermal profile of a defectively operating apparatus having multiple control zones, e.g., an injection molding manifold, and the thermal profile is used in determining why the apparatus is operating defectively, e.g., not operating optimally or effectively or according to expectations or specifications or otherwise malfunctioning. In certain such embodiments, the results of such determination are utilized to determine a design change or other steps to correct the deficiency. One skilled in the art will readily appreciate that one or more of the steps or features of the methods and systems disclosed here may be carried out by computer-executable instructions stored on one or more computer-readable mediums.

[0015] Those of ordinary skill in the art will recognize and understand from this disclosure and the further discussion below, various alternative and optional additional features and advantages of the methods and systems disclosed here for implementing finite element analysis in the design or analysis of apparatus having multiple thermal control zones. Also, additional aspects and advantages of the present invention will be apparent to those skilled in the art from the following detailed description of certain embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The following detailed discussion of certain select embodiments will refer to the appended drawings in which:

[0017] FIG. 1 is a flowchart of an exemplary finite element analysis method or system according to one aspect of the invention, for determining the thermal profile of an apparatus having multiple thermal control zones.

[0018] FIG. 2a shows a perspective view of an exemplary model of a multi-component injection molding manifold having multiple thermal control zones, which may be analyzed by a finite element analysis method or system according to certain exemplary embodiments of the invention.

[0019] FIG. 2b is a perspective view of an exemplary modeled portion of a manifold having multiple thermal control zones, which may be analyzed by a finite element analysis method or system according to certain exemplary embodiments of the invention.

[0020] FIG. 3a is an exemplary thermal matrix providing exemplary data to illustrate a finite element analysis method or system according to certain exemplary embodiments of the invention.

[0021] FIG. 3b is an exemplary temperature matrix of a manifold having three control zones, providing exemplary data to illustrate a finite element analysis method or system according to certain exemplary embodiments of the invention.

[0022] FIG. 4 is a perspective view of an exemplary thermal profile of a portion of a manifold system having more than one control zone, utilizing the data shown in FIG. 3b.

DETAILED DESCRIPTION OF CERTAIN EXEMPLARY EMBODIMENTS

[0023] The exemplary methods and systems herein are further disclosed and described below in the context of industrial injection molding manifolds for ease of understanding only, however, one skilled in the art will readily understand that other applications, industrial or otherwise, are within the scope of the invention. Thus, the finite element methods and systems of the present disclosure are useful in analyzing or designing any apparatus having multiple thermal control zones. As used here, the term apparatus is used broadly to mean apparatus, devices, assemblies, sub-assemblies and the like.

[0024] FIG. 1 is an exemplary flowchart of a method of analyzing the design of a manifold according to one aspect of the invention. The applicability of FIG. 1 and the description below to system embodiments of the present invention will be readily apparent to those of ordinary skill in the art given the benefit of this disclosure. As one skilled in the art will readily appreciate, the method may be modified to include fewer or additional steps according to various embodiments of the invention. The method of FIG. 1 can be utilized to determine the design of a manifold, e.g., to develop a suitable design for a manifold. Further, the method may be utilized to analyze the design of an existing manifold, e.g., to develop a thermal profile comprising estimated temperature gradients within the manifold under a defined set of conditions, e.g. under the manifold's normal operating conditions. The method may also be modified according to the teachings of this disclosure to redesign an existing manifold. This would be particularly advantageous when an existing manifold is not operating properly or efficiently. For example, scorching or improper flow of injection molding material may be due to temperatures in one or more of the zones of the manifold (at some or all times during the injection molding cycle) which are too high or too low. Adjusting the thermal controller for that zone may or may not be suitable or sufficient to correct the problem. For example, adjusting the thermal controller for that zone may not be suitable or sufficient if it is being adversely affected by the thermal properties (e.g., the temperature) of one or more of the other control zones. One or more methods as disclosed and described here may be utilized to determine the source of the problem, provide a result to suggest a particular retrofit or adjustment to remedy the problem,

and/or aid in the design of such a retrofit. Such adjustment may, for example, be in the design of the manifold and/or in the manner in which it is operated, including, e.g., the temperature set points of the zone controllers, etc.

[0025] At exemplary step 102 of FIG. 1, a model of an apparatus, such as a manifold system, having a plurality of thermal control zones is received. As used herein, each thermal control zone of the manifold has at least one thermal input and at least one thermal output. According to one embodiment of the invention, each thermal control zone comprises a thermal controller and a thermal device. The thermal controller typically is configured to transmit a control signal (or not transmit such a signal), in response to a thermal parameter at a specific location within the manifold, e.g., a thermocouple or other temperature sensor adapted to transmit or not transmit a signal in response to the temperature of the manifold at the location of the sensor in the zone in question being below or above a set point. The signal may be transmitted by the sensor directly to the thermal device, i.e., to the thermal device or to an associated microprocessor or the like or other circuitry to cause ultimately a corresponding actuation or de-actuation of the thermal device. It should be understood in this regard that, while a single microprocessor or the like or other circuitry may be used to receive and process control signals from the sensors or other controllers of multiple zones, the control signal from the thermal controller of a particular zone is the sole or primary control signal for the thermal device(s) of that particular control zone. As used herein, a thermal device for a zone may be any device operative under the control of the associated controller to heat or cool the zone, for example, an electric, fluidic or other heater, thermoelectric cooler, heat sink, heat pipe, or any combination thereof. In essence any component or group of components that is intentionally configured to provide or remove thermal energy from the control zone may be a thermal device.

[0026] As used herein, an apparatus or system may comprise one or more components that are in thermal communication with each other. FIG. 2a shows an exemplary model of multi-component manifold that may be employed according to one implementation of step 102 of FIG. 1. Manifold system 200 includes manifold 202 and manifold 204 which, in turn, can be conceptually divided into multiple thermal control zones for analysis in accordance with the methods and systems disclosed here. Each of the multiple thermal control zones has a thermal controller and an associated thermal device. As shown, manifold 202 includes thermal device 206 and thermal controller 208.

[0027] The model of manifold system 200 may be configured such that thermal controller 208 detects, measures, receives or otherwise determines a thermal parameter of or corresponding to its thermal zone, such as the temperature of the manifold at thermal controller 208 or the temperature of resin or other molding material fed through channel 210 of the manifold to molding cavities. In certain other exemplary embodiments, multiple thermal controllers may be utilized in a thermal control zone to detect, measure, receive or otherwise determine the thermal parameter(s) at multiple locations within the zone. The control signals from such multiple controllers may be used collectively (e.g., with averaging or other combination or selective elimination, etc.), serially, or otherwise to control the heater or other thermal device of the zone.

[0028] Other thermal parameters, i.e., other determinable values or parameters corresponding to the temperature or other suitable thermal property of the zone, may be utilized, such as but not limited to conduction, convection, radiation, and/or internal heat generation. In response to the thermal parameter at a specific location within the apparatus, thermal controller 208 is configured to transmit a control signal directly or indirectly to thermal device 206 located within the same control zone as thermal controller 208. As noted above, the control signal may be fed directly to the thermal controller or may utilize an indirect connection, such as via a microprocessor or the like. As will be appreciated by those skilled in the art, such a process may be partly or wholly implemented through the use of computer-executable instructions stored on one or more computer-readable mediums that are in electronic communication with one or more such processors.

[0029] Thermal device 206 and any associated circuitry, devices or the like, including, e.g., electrical power feed means, etc., is operable in response to the control signals from (directly or indirectly, as discussed above) associated thermal controller 208. The control signal may, e.g., alter the operating state of thermal device 206, such as increasing or reducing the power supplied to thermal device 206, initiating, terminating or otherwise adjusting the flow of heating or cooling fluid to or through thermal device 206, etc. For example, if the thermal device is a heater, reducing the power may reduce the heat emitted by thermal device 206. In other embodiments, the control signal may merely switch the power state of thermal device 206 between an "ON" state and an "OFF" state.

[0030] Returning to FIG. 2a, manifold 204 comprises thermal device 212 that is associated with thermal controller 214 and thermal device 216 that is associated with thermal controller 218. Therefore, manifold 204 comprises at least two thermal control zones or at least a portion of each of at least two control zones. As seen in FIG. 2a, portions of manifold 202 are in close proximity to thermal device 212 and thermal controller 214 of manifold 204. In fact, location 220 of manifold 204 is proximate to portions of manifold 202. Therefore, in one embodiment, portions of manifold 202 may be considered in the same control zone as portions of 204. Alternatively, the manifold system can be divided into a different set of thermal control zones. In select embodiments, the thermal control zones are symmetric with respect to each other, whereas in other embodiments, the control zones are determined by a myriad of factors. It will be within the ability of those of ordinary skill in the art, given the benefit of this disclosure, to suitably divide a manifold or other apparatus into multiple control zones for design or analysis in accordance with the finite element methods disclosed here.

[0031] Also located on manifold 204 of model 200 is thermal device 216 and thermal controller 218, which both belong to the same control zone, specifically, a control zone different from that of thermal device 212 and thermal controller 214. In addition to being primarily thermally controlled by its own thermal device and thermal controller, the temperature and/or other thermal properties or performance of each such control zones are affected by the inputs of the thermal device of the other control zone as well as possibly the inputs of thermal device 206.

[0032] As shown, model 200 is in graphical form, however, one skilled in the art, given the benefit of this disclo-

sure, will readily appreciate that the model and any information relating to the model provided in step 102 may be in any form, including graphical, numerical, binary, and combinations thereof so long as the model includes or represents or is based on or otherwise incorporates at least one aspect of the physical geometry of the system which it represents. The received data may represent a 2-dimensional model or a more complex 3-dimensional model.

[0033] Returning to FIG. 1, at least one input regarding at least one material of the apparatus or system represented by the model utilized in step 102 (such as model 200), is provided in step 104. The input may be a manual user-input providing information regarding one or more materials, chemicals or compositions utilized or intended to be utilized to make the physical system. The information may, for example, be one or more physical or performance properties, e.g., thermal conductivity, heat capacity or thermal capacitance, specific heat capacity (also called more properly "mass-specific heat capacity" or more loosely "specific heat"), boundary conditions, or the like, etc. In one embodiment where the model is directed towards a system that is already designed, the materials may be detected by automated mechanisms or automatically submitted to the model. In still yet further embodiments, the input is provided as part of step 102. The input may be in any suitable form, e.g., textual, numerical, binary or combinations thereof, and optionally is converted to another form for use within the process.

[0034] The input may be the value of a single physical or performance property or a value representing multiple physical or performance properties in any suitable combination. Multiple inputs may be received regarding the same material, such as the material's composition, heat capacity, specific heat capacity, thermal conductivity, density, strength, etc. In other exemplary embodiments, only one input is received and may then be associated with several qualities of the material, e.g., qualities that are stored on a computer-readable medium. In yet other exemplary embodiments, one or more inputs are received for multiple materials that make up the apparatus or system. For example, manifold 202 of model 200 may comprise one or more materials not included in manifold 204, and inputs may be received for each.

[0035] In step 106, a mesh for the model, such as model 200 is defined. As readily known to those skilled in the art, a plurality of nodes are mapped or otherwise distributed around the modeled topography of the system or select areas of the system of interest. The nodes are interconnecting, wherein each node is modeled to be in communication with and to be affected by any changes to at least one other node it is in communication with. The quantity, distribution, and density of the nodes for any given determination (i.e., analysis or design) in accordance with the methods and systems disclosed here may be determined by those of ordinary skill in the art given the benefit of this disclosure, based on factors, including but not limited to, the desired accuracy of the result, geometry of one or more components of the apparatus being analyzed, the material(s) used in the apparatus or its component(s), the design of the apparatus or system, and/or other areas of specific concern applicable to the particular analysis. In certain exemplary embodiments, each control zone is represented by a fixed number of nodes ranging from 1 to a maximum quantity, yet in other embodiments, different quantities of nodes are assigned to various

control zones based upon one or more factors, such as those described above. In certain exemplary embodiments, the mesh is created automatically by computer-executable instructions stored on a computer-readable medium. In certain such embodiments, manual manipulation may be conducted to further refine the mesh. Those skilled in the art, given the benefit of this disclosure, will be well able to implement suitable procedures for defining and manipulating a mesh as used herein.

[0036] FIG. 2b shows a perspective view of a portion of exemplary model of a manifold that may be utilized according to select embodiments of the invention. As shown, the exemplary portion of model 250 comprises a mesh 252 that, when viewed graphically, appears similar to a net or spider-web that covers the outer surface of the model 250. The mesh 252 divides the model 250 into discrete elements that are all interconnected, with proximate nodes being in contact with neighboring nodes. As presented in the exemplary example, the nodes are not necessarily symmetrically spaced, and have different shaped boundaries. As further seen with exemplary mesh 252, some elements may be larger than others elements in addition to having different shapes.

[0037] In step 108, one or more factors relating to boundary conditions may be introduced into process. As used herein, boundary conditions may encompass or include any known parameters that introduce, remove, alter, and/or affect the distribution of a thermal parameter in the system. For example, the specific location of a nearby conductive manifold or other mechanism that affects a temperature condition may be inputted into the system to compensate for any heat loss due to the conductive manifold. As used throughout the specification, the term heat loss may encompass a positive or negative value to indicate a gain of heat energy or the loss of heat energy. Also, the outer boundaries of the manifold may be exposed to ambient air temperatures at one location while exposed to extreme temperatures at another, such as being in close proximity to another manifold or section of the system that is known to affect one or more temperature parameters.

[0038] Yet in another embodiment, a specific protrusion or attached component, made of the same or a different material as one or more manifolds, may affect one or more temperature parameters. For example, looking to FIG. 2a, contact plate 226 is operatively attached to manifold 202. In one embodiment, the heat lost by contact plate 226 is readily known or may be estimated and therefore may be provided to the system as an input as a known boundary condition. As one skilled in the art will readily appreciate given the disclosure provided herein, according to one embodiment, one or more boundary conditions may initially be an unknown factor that may be calculated according to the teachings of select aspects of the invention. For example, in one embodiment, a temperature parameter of several control zones may be known in a manifold that has already been designed and/or manufactured. However, it would be desirable to determine the effect of a boundary condition, such as the addition of contact plate 226, may have upon the system. As demonstrated from the foregoing, there may be a plurality of boundary conditions that may differ across different portions of one or more components of an apparatus. As would be further appreciated by one skilled in the art, one or more boundary conditions may be considered in step 104, when the material data is provided.

[0039] In step 110, the determination of thermal correlation between a plurality of zones is initiated. One exemplary method of determining the thermal correlation is shown by way of the illustrative thermal influence matrix of FIG. 3a. The exemplary thermal matrix 300 is formed by an $[n \times n]$ matrix, wherein “n” equals the number of control zones. Exemplary thermal matrix 300 provides exemplary data to illustrate one process according to these aspects of the invention. As seen with column 302, a fixed simulation process is conducted. The term fixed simulation signifies that the number of simulations performed is equal to the number of thermal control zones ($n = \#$ of simulations). Columns 304, 306 and 308 represent the specific control zones Htr_1, Htr_2, and Htr_3, respectively, which for example, may represent heaters 206, 212, and 216 shown in FIG. 2a. As discussed above, however, the control zones may be any set of areas that each has at least one thermal input and at least one thermal output. The thermal input for a given zone may be, for example, a value corresponding or correlating to the rate of heat loss from that zone under operating conditions at a given temperature, e.g., at the temperature set point of the thermal controller of the zone in question. In a typical application, therefore, the temperature may, for example, be the temperature at that zone’s thermal controller, recognizing that a temperature gradient may exist in the zone from the location of the thermal controller to any other location in the zone. The thermal input for a given zone may be, for example, a value corresponding or correlating to the rate of heat input into that zone by the thermal device of that zone, upon actuation, under operating conditions.

[0040] The thermal relationship between each zone may be quantified by applying an arbitrary value for a thermal parameter to one particular zone, while the other zones are unaltered. For each simulation, which will be equal to the number of control zones tested, the arbitrary value will remain the same. For example, looking to simulation 1, designated by row 310, value “q” is applied to control zone Htr_1 while the two other exemplary control zones remain unaltered. For simulation 2, designated by row 312, value “q” is applied to control zone Htr_2, while Htr_1 and Htr_3 are unaltered, and looking to simulation 3, designated by row 314, “q” is applied to Htr_3 and the other two control zones are left unaltered. Thus, for each simulation, “q” is applied to a single control zone that is different than the previous simulation, where the number of simulations equals the number of thermal control zones. In other implementations, another value that is different than “q” may be applied, but the same value will be applied for each simulation, albeit at different control zones.

[0041] Columns 316, 318 and 320 provide the results for each control zone per simulation using the nomenclature T_{xy} , where T designates a temperature value is given, “x” designates the control zone for which T is being measured and “y” designates the control zone that is causing the provided value. For example, in Simulation #1 where “q” was only applied to control zone 1 (Htr_1), the effect of “q” was measured for each control zone, including the zone for which it was applied. As seen in column 316, the value is T11, thus providing the temperature at control zone 1 from the application of “q” at Htr_1. Column 318 for the same simulation has a value T21, thus providing the temperature at control zone 2 from the application of “q” at Htr_1 and column 310 has a value of T31, thus providing the temperature at control zone 3 from the application of “q” at Htr_1.

As predicted, for Simulation #2, the “y” will always be 2 and accordingly, will always be 3 for the Simulation #3.

[0042] Those skilled in the art will readily understand that any thermal parameters, such as those described in this application, as well as those known in the art, may be utilized without departing from the scope of the disclosure. To better acquaint the reader with a real-world example, FIG. 3b is provided as an exemplary temperature matrix of a manifold having three control zones providing exemplary data to illustrate another process according to select embodiments of the invention. As seen in FIG. 3b, “q” is set to 0.1 W/mm², where “q” is the arbitrary heat flux value corresponding to the heater for each of the three zones (during the 3 simulations). For each of the three simulations, the temperature is recorded at each thermal controller’s location (1 per control zone) and the influence matrix shown on the right side of FIG. 3b may be calculated with the provided data, wherein each column provides the simulated temperature at each thermal controller due to the heat flux applied to the heater designated in that particular column.

[0043] Step 112 may then be implemented, where a thermal parameter for each control zone is applied. According to one embodiment, the thermal parameter is the temperature of a section of the manifold or fluid traveling within the manifold at a specific location. For example, as shown in FIG. 2a, thermal controller 208 may provide a temperature value at its location. In other embodiments, thermal controller 208 receives or measures the thermal parameter of a compound, such as a liquid in channel 210, as the liquid travels through a portion of the control zone. One skilled in the art understands that any parameter relating to a thermal property that is known regarding a plurality of individual control zones of interest may be utilized in step 112.

[0044] At step 114, the influence matrix may be utilized to obtain a result of the linear thermal relationship of an unknown thermal parameter for each control zone within the influence matrix. Using the manifold model 200 of FIG. 2a and influence matrix 300 of FIG. 3 as an example, in one embodiment Equation (1) may be utilized to determine the steady-state heat conduction with the three zones when the control zone input is a temperature, such as heat produced by thermal device 206, and the control zone output is a heat flux (which is unknown)

Equation (1):

$$T_{ic(1...3)} = \{I_{temp}\} \times q_{(1...3)}$$

[0045] Looking to Equation 1, “T” is the temperature at the thermal controller, “q” is the heat flux, and “I” represents the influence matrix. In the exemplary embodiment, the input parameter “T” is known and provided from step 112, therefore, the equation is to be solved for the output parameter “q”. Thus, in one embodiment, the equation may be used to determine how much heat needs to come from a heater to get a certain temperature at a thermal controller. As one skilled in the art will readily appreciate, derivations of Equation 1 may be utilized to obtain a result of the linear thermal relationship of the unknown thermal parameters for each control zone within the influence matrix without departing from the scope of the recited aspects of the invention. In one embodiment, FIG. 3a may be utilized to determine output parameter “q”.

Equation (2):

$$\begin{Bmatrix} q1 \\ q2 \\ q3 \end{Bmatrix} = \begin{bmatrix} T11 & T12 & T13 \\ T21 & T22 & T23 \\ T31 & T32 & T33 \end{bmatrix}^{-1} \begin{Bmatrix} Tset - Tplate \\ Tset - Tplate \\ Tset - Tplate \end{Bmatrix}$$

Utilizing the “real-world data” presented in the exemplary influence matrix of FIG. 3b, Equation 2 may be expressed as:

$$\begin{Bmatrix} q1 \\ q2 \\ q3 \end{Bmatrix} = \begin{bmatrix} 680 & 684 & 293 \\ 255 & 846 & 636 \\ 63 & 232 & 1049 \end{bmatrix}^{-1} \begin{Bmatrix} 288 - 82 \\ 288 - 82 \\ 288 - 82 \end{Bmatrix}$$

where Tset=288 and Tplate=82, thus providing a result of:

$$\begin{Bmatrix} q1 \\ q2 \\ q3 \end{Bmatrix} = \begin{bmatrix} 0.0163 \\ 0.0065 \\ 0.0172 \end{bmatrix} W/mm^2$$

[0046] One skilled in the art will readily understand with aid of this disclosure derivations of Equation 2 that will adequately determine “q” or any other thermal value. For example, in one embodiment, {−Tplate} may be removed from the equation if delta T is not required or desired. In yet further embodiments, other components and computations may be added to the equation being utilized to tailor the process for specific purposes.

[0047] Once the thermal parameter, such as the heat flux is determined, step 116 may then be applied to the FEA model to determine the thermal profile of the system or portion of the system in question. For example, the heat flux obtained for each control zone may be applied to the heaters for the respective control zones in a finite element analysis to simulate the correct thermal profile. FIG. 4 is a perspective view of one exemplary thermal profile of a manifold system utilizing the data shown in FIG. 3b. Yet in other embodiments, where a new system may be in the process of being designed, the profile obtained may be useful in further development or design of the system, such as a multi-component manifold. Indeed, step 116 may be initiated to determine why a manifold already manufactured is not operating at optimal level or otherwise malfunctioning. In one such embodiment, the results of step 116 may be utilized to determine how to fix the deficiency. For example, if one control zone’s thermal properties are adversely affecting the thermal properties of another control zone, a thermal device may be added to remedy or fix the deficiency. In yet another embodiment, an existing thermal device may be altered to fix the deficiency.

[0048] The foregoing detailed description of preferred embodiments is intended to be exemplary of the invention and illustrative. Modifications of the embodiments disclosed and alternative embodiments will be apparent to those skilled in the art in view of the above, and all such modifications and alternatives are intended to be within the scope of appropriate ones of the following claims. The appended claims are intended to cover all such modifications and

alternative embodiments. It should be understood that the use of a singular indefinite or definite article (e.g., “a,” “an,” “the,” etc.) in this disclosure and in the following claims follows the traditional approach in patents of meaning “at least one” unless in a particular instance it is clear from context that the term is intended in that particular instance to mean specifically one and only one. Likewise, the term “comprising” is open ended, not excluding additional items, features, and elements.

What is claimed is:

1. A method of determining a thermal parameter of an apparatus, the method comprising:

- (a) providing a model of an apparatus having a plurality of thermal control zones, each thermal control zone of the apparatus comprising a thermal controller and a thermal device, wherein the thermal controller of each thermal control zone is operative, in response to a thermal parameter at a location within that thermal control zone, to generate a control signal directly or indirectly to the thermal device of that thermal control zone;
 - (b) providing at least one input value that directly or indirectly corresponds to at least one thermal property of at least one material of the apparatus;
 - (c) defining a finite element analysis mesh having nodes for the model of the apparatus;
 - (d) applying at least one boundary condition value to at least one portion of the model of the apparatus;
 - (e) determining the thermal correlation among at least a selected plurality of the thermal control zones, comprising constructing an $[n \times n]$ influence matrix of matrix values, where n equals the number of selected thermal control zones, each matrix value corresponding to a value of a first thermal parameter selected from heat loss and temperature for a corresponding one of the thermal control zones, the constructing of the $[n \times n]$ influence matrix comprising conducting n finite element analysis simulations of the apparatus based on the finite element analysis mesh, the input value of (b) and the boundary condition value, each of the n finite element analysis simulations comprising determining a matrix value of the first thermal parameter for each thermal control zone by applying a value for the other thermal parameter selected from heat loss and temperature which is unknown to each boundary of a corresponding one of the thermal control zones; and
 - (f) using the finite element analysis influence matrix to determine the value of the second thermal parameter for each control zone for a desired value of the first of the first thermal parameter for each control zone included in the selected plurality of thermal control zones.
2. The method of claim 1, further comprising:
- (g) applying the result obtained in (f) to a finite element analysis simulation the model of (a) to obtain a thermal parameter for the apparatus.
3. The method of claim 1, further comprising:
- (g) applying the result obtained in (f) to an finite element analysis simulation the model of (a) to obtain a thermal profile for the apparatus.
4. The method of claim 3, further comprising:
- (h) utilizing the thermal profile of (g) to evaluate a malfunction in an existing apparatus.

5. The method of claim 1, wherein the thermal device is selected from the group consisting of: a heater, thermoelectric cooler, heat sink, heat pipe, and combinations thereof.

6. The method of claim 1, wherein the apparatus is a manifold configured to transport a material that is a fluid.

7. The method of claim 6, wherein the manifold comprises a plurality of components and wherein at least a portion of the plurality of components comprise one control zone.

8. The method of claim 1, wherein Equation (1) is utilized in association with the influence matrix to obtain a linear thermal relationship, wherein the unknown thermal parameter for each thermal control zone is the heat flux and the known first thermal parameter is a temperature value at the thermal controller for each thermal control zone, thereby determining how much heat needs to come from a thermal device in a specific thermal control zone to get a certain temperature at the thermal controller in the same thermal control zone.

9. The method of claim 1, wherein the input value of (b) further corresponds to a thermal property of a node of the mesh defined in (c).

10. The method of claim 1, wherein the input value of (b) further corresponds to a thermal property of a thermal control zone of the apparatus.

11. A method comprising:

- (a) receiving a model of an apparatus having a plurality of thermal control zones, each thermal control zone of the apparatus comprising a thermal device controlled by a thermal controller, wherein each thermal controller is configured to transmit, in response to a thermal parameter at a specific location within the apparatus, a control signal to the thermal device;
- (b) providing at least one input value that directly or indirectly corresponds to at least one thermal property of at least one material of the apparatus;
- (c) defining a finite element analysis mesh having nodes for the model of the apparatus;
- (d) applying at least one boundary condition value to at least one portion of the model of the apparatus;
- (e) determining the thermal correlation among at least a selected plurality of the thermal control zones, comprising constructing an $[n \times n]$ influence matrix of matrix values, where n equals the number of selected thermal control zones, by applying a known thermal parameter for each control zone within the influence matrix and conducting n simulations, wherein the constructing of the $[n \times n]$ influence matrix comprising conducting n finite element analysis simulations of the apparatus based on at least the finite element analysis mesh and the input value of (b) and the boundary condition value; and
- (f) using the influence matrix to obtain a result of the linear thermal relationship of an unknown thermal parameter for each control zone within the influence matrix

12. The method of claim 11, wherein the thermal controller is within the same thermal control zone as the thermal device it is controlling.

13. The method of claim 11, further comprising:

- (g) receiving at least one user input that modifies the mesh defined in (c).

14. The method of claim 11, further comprising:

- (g) applying the result obtained in (f) to the model of (a) to obtain a thermal profile for the apparatus.

15. The method of claim 14, further comprising:
(h) utilizing the result obtained in (g) to evaluate a malfunction in an existing apparatus.
16. The method of claim 14, further comprising:
(h) utilizing the result obtained in (g) in designing a physical apparatus of the model received in (a).
17. The method of claim 11, wherein the known thermal parameter for each thermal control zone comprises the temperature at the thermal controller.
18. The method of claim 11, wherein the known thermal parameter for each thermal control zone comprises the heat loss across a boundary of the control zone.
19. The method of claim 11, wherein Equation (1) is utilized in association with the influence matrix to obtain the linear thermal relationship, wherein the unknown thermal parameter for each control zone is the heat flux and the known thermal parameter is a temperature value at the thermal controller for each thermal control zone, thereby determining how much heat needs to come from a heater in a specific thermal control zone to get a certain temperature at the thermal controller in the same thermal control zone.
20. The method of claim 11, wherein the apparatus is a manifold having a plurality of channels configured to transport a fluid.
21. The method of claim 11, wherein the input value of (b) further corresponds to a thermal property of a node of the mesh defined in (c).
22. A system comprising:
a computing device having a computer-readable medium configured to receive computer-executable instructions that when executed provide a model of an apparatus having a plurality of thermal control zones, each thermal control zone of the apparatus comprising a thermal device controlled by a thermal controller, wherein each thermal controller is configured to transmit, in response to a thermal parameter at a specific location within the apparatus, a control signal to the thermal device;
an input device operatively coupled to the computing device configured to allow the reception of at least one input regarding at least one material of the apparatus and an input relating to at least one boundary condition;
a computer-readable medium having computer-readable instructions for defining a mesh having nodes for the model of the apparatus; and
a computer-readable medium having computer-readable instructions that when executed construct an $[n \times n]$ influence matrix, where n equals the number of selected thermal control zones, each matrix value corresponding to a value of a first thermal parameter selected from heat loss and temperature for a corresponding one of the thermal control zones, the constructing of the $[n \times n]$ influence matrix comprising conducting n finite element analysis simulations of the apparatus based on the finite element analysis mesh, the input value of (b) and the boundary condition value, each of the n finite

- element analysis simulations comprising determining a matrix value of the first thermal parameter for each thermal control zone by applying a value for the other thermal parameter selected from heat loss and temperature which is unknown to each boundary of a corresponding one of the thermal control zones and using the finite element analysis influence matrix to determine the value of the second thermal parameter for each control zone for a desired value of the first of the first thermal parameter for each control zone included in the selected plurality of thermal control zones.
23. The system of claim 22, further comprising:
a computer-readable medium having computer-readable instructions that when executed apply the result of the linear thermal relationship to the model to obtain a thermal profile for the apparatus.
24. The system of claim 23, further comprising:
a display adapter operatively coupled to the computing device for displaying the thermal profile of the apparatus.
25. The system of claim 23, further comprising:
a computer-readable medium having computer-readable instructions that when executed analyze the thermal profile of the apparatus to evaluate any malfunctions of a physical apparatus having characteristics that are similar to the model.
26. The method of claim 25, wherein the apparatus is a manifold having a plurality of channels configured to transport a fluid.
27. The method of claim 26, wherein the apparatus is a manifold having a plurality of channels configured to transport a material that is a fluid at an elevated temperature and a solid at a lowered temperature.
28. The system of claim 23, further comprising:
a computer-readable medium having computer-readable instructions that when executed utilize the thermal profile of the apparatus in designing a physical apparatus having characteristics that are similar to the model.
29. The system of claim 23, wherein the known thermal parameter for each thermal control zone comprises the temperature at the thermal controller.
30. The method of claim 23, wherein the computer-readable medium having computer-readable instructions that when executed construct an $[n \times n]$ influence matrix comprises instructions for performing Equation (1) in association with the influence matrix to obtain a linear thermal relationship, wherein the unknown thermal parameter for each thermal control zone is the heat flux and the known first thermal parameter is a temperature value at the thermal controller for each thermal control zone, thereby determining how much heat needs to come from a thermal device in a specific thermal control zone to get a certain temperature at the thermal controller in the same thermal control zone.

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